DETERMINATION OF SHEAR PROPERTIES OF COMPOSITES THROUGH IOSIPESCU TEST

by

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CERTIFICATE

This is to certify that the thesis entitled, " DETERMINATION OF SHEAR PROPERTIES OF COMPOSITES THROUGH IOSIPESCU SHEAR TEST " by Appu Kuttan Plakkot is a record of the work carried out under our supervision and has not been submitted elsewhere for a degree

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TABLE OF CONTENTS

ABSTRACT

An Iosipescu shear test fixture has been fabricated. Shear tests have been performed on glass, Kevlar and carbon fibre reinforced epoxy composites. All the tests were performed on MTS servo-hydraulic testing system in compression mode. The test fixture developed was also used to determine the shear mode fracture toughness of random glass composite.

Shear modulus and shear strength were found for the above mentioned materials. The effect of fibre orientation on shear behavior was studied for unidirectional carbon composites. The shear modulus of carbon composites were predicted theoretically for different fibre angles and compared with the experimental values. Failure and fracture behaviour were studied macroscopically for the present materials. The results of Iosipescu shear tests were interpreted on the basis of fracture studies and type of reinforcement used. The shear mode fracture toughness tests were performed on random glass composites. Their fracture was found to deviate from pure Mode II. These specimens showed a mixed mode fracture with Mode II domination. Shear mode fracture toughness J_{IIc} was determined using J-integral approach. The value of 'J' was found to vary with the crack length.

CHAPTER 1

INTRODUCTION

1.1 COMPOSITE MATERIALS :

The word composite means "consisting of two or more distinct parts". Thus materials having two or more distinct constituents, on a macroscale having distinct interface separating them are called composite materials. The composites achieve certain physical properties not realizable by the constituent materials individually. These materials offer high specific strength and stiffness. Oriented fibrous composites also offer controlled anisotropy. The manufacture of composites requires comparatively low labour and generate less wastage in addition to the ease of processing of complicated structural forms. Composite structures are destined to many future applications, especially in aerospace and transport industry due to their such properties as good fatigue and corrosion resistance, low heat conductivity,good electrical insulation properties, favourable cost effectiveness etc. Also in the recent past extensive research on the manufacture, characterization, fatigue and fracture of these materials have increased the confidence in the use of these materials and thus they have replaced conventional materials in many applications.

1.2 CHARACTERIZATION OF COMPOSITE MATERIALS :

The use of continuous-fibre-reinforced composites as high performance structural materials in modern aerospace vehicles necessitates the accurate measurement of the material response to

mechanical and thermal loads. The ability to predict the mechanical behaviour of fibre-reinforced composites is in a state of development. Requirements necessary for adequate predictions are reliable material data (moduli, poissons ratios and failure strengths), a suitable failure criterion and an accurate component model. Also understanding the material response over the entire range of load is necessary if advanced design procedures are employed for efficient material utilization.

The most popular and successful analytical tool for both characterization purposes and stress analysis is laminated plate theory. Fundamental to lamination theory are the properties of a single ply. Usually, individual lamina are assumed to be homogeneous, orthotropic and in a state of plane stress. It is therefore necessary to test single laminae in plane stress in order to obtain mechanical properties and failure criteria. Most of the current composite material test methods were originally developed for isotropic materials. Coupling effects, nonlinear behaviour of the matrix or the fibre-matrix interface and the presence of normal stresses combine to make the present test methods questionable for orthotropic materials.

As such, only four material properties are required,i.e., stress-strain response in the fibre direction and normal to fibre directions for a load in the respective direction, the strain response normal to the fibres for a load in the direction of fibres or vice versa, and the inplane shear response of the lamina. The first three properties can be easily obtained by performing uniaxial tension test. The last property, the inplane shear behaviour is relatively difficult to obtain and subject to considerable

controversy primarily due to the problems encountered in achieving a state of uniform pure shear. The inplane properties of fibrous composites can be varied by controlling the material (direction of fibres, volume fraction etc.) and manufacturing variables (process, curing time etc.). But they are generally weak in inplane shear. This make the inplane shear response of composite materials critical.

A variety of test methods exist for introducing shear stress in materials. Some tests use filament wound composites or unidirectional rods. But most of the use of composite materials are in the form of a laminae and differ in mechanical properties from that of tube or rod because the fabrication procedure is entirely different. Thus for testing flat specimens a number of test methods were emerged. The loading scheme and specimen geometry used in most of the cases caused intrusion of normal or bending stresses, stress-concentration and other undesirable effects in the test region which made these tests less than ideal. Because, they affect the shear modulus measurement by disturbing the shear stress distribution in the test region and the shear strain measured can be erroneous. Also in shear strength tests, the final failure may not be in shear mode, giving questionable shear strength results.

The ideal shear test method should provide a region of pure uniform shear stress. There should be a unique relation between the applied load and magnitude of shear stress in the test section. Further for accurate determination of shear stress/strain response the test section should be one of maximum shear stress relative to all other regions of the specimen. In addition they should give

reproducible results, relatively simple to conduct, require small, easily fabricated specimens and is capable of measuring both shear strength and shear stiffness simultaneously.

An early evaluation of different shear test methods for composites have been done by Chio et. al. [1]. Yeow and Brinson [2] did a comparative study of simple shear characterization methods for composite laminates. A brief survey of available shear-test methods suitable for composite materials can also be obtained from Ref. 3 and 4. A recent review and evaluation by Lee and Munro [5] gives us a more complete comparison of shear tests available for composites. Based on the above mentioned papers and other published literatures, almost all the existing in-plane shear test methods are briefly discussed and compared in the following section.

1.3 LITERATURE SURVEY :

The most uniform shear-stress state can be achieved in a material by applying torsional loading to a thin walled tube specimen. Whitney [6] stated that the torsion tube test is most suitable from an applied mechanics point of view. Rizzo and Vicario [7] reported that strength values may be influenced by gripping the ends of the tube. The uniformity of the state of stress produced for tubular laminated specimens depends on the anisotropy as well as the geometry. The main drawback of this testing is the difficulty associated with fabricating and testing of tubular specimens. A similar test method subjects solid composite bars to torsion loads but they also require special fabrication technique and the test is limited to unidirectional materials.

Whitney [8] conducted an extensive theoretical stress

analysis of two rail specimens and Sims [9] for three rail symmetric shear test. Gracia [10] analytically determined how various geometric parameters influenced the magnitude and distribution of inplane normal and shear stresses in a two rail shear specimen. Bergner [11] investigated the three rail shear test using finite element analysis and concluded that rail configuration produce region of uniform shear stress over most of the test sections but they are also accompanied by normal stresses depending on the stiffness of rails, the method of load applications and the laminate properties. Thus these studies concluded that rail shear test induce stress concentrations at the specimen edges, producing questionable shear strength values. Specimen installation is also somewhat cumbersome.

Another method for shear testing is the picture frame test. Dustin et. al. [12] reported that reliable initial modulus and ultimate strength values could be obtained for fibre glass $[0^{\circ}/90^{\circ}]_s$ specimens. Bryan [13] made photoelastic investigations and concluded that the stress distribution deviated substantially from pure shear thus not appreciated for determining inplane shear modulus, but is an accurate method for determining inplane shear strength as the shear stress state was essentially uniform pure shear at the critical region (which is along the edge). Thus a general conclusion is made that the sample has no significant section, the state of stress is not homogeneous and only a small part of the sample is subjected to pure shear.

The $\pm 45^{\circ}$ off axis tension coupon is a simple test method. Rosen [14] developed expression for a $\pm 45^{\circ}$ fibre composite

laminate uniaxially loaded in 0° direction, the lamina longitudinal shear stress in fibre direction is statically determinate and is equal to half of the externally applied uniaxial stress. Hahn [15] pointed out that this is possible only if there is no shear coupling even for symmetric laminates and the layers should be stacked as homogeneous arrangement as possible. Chio et. al. [1] and Yeow [2] recommended the $\pm45^{\circ}$ specimen for determining the stress/strain response in shear. Petit [16] checked the stress/strain results of a $\pm45^{\circ}$ laminate and compared it with cross-beam test. He concluded that the primary importance of this method is to determine the elastic shear modulus and not for inelastic shear behaviour because of interaction effects of shear with normal stresses.

Chamis and Sinclair [17] proposed the 10° off axis tensile shear test. They found during the 10° off axis tensile test of graphite epoxy composite that the inplane shear stress approaches or reaches a maximum value. This test method gives uniform shear stress through the thickness, thus adopted for environmental tests, characterization of fatigue and dynamic loading cases etc. Chio et. al. [18] evaluated it with aramid epoxy composites and found significant shear coupling and that it give a higher shear modulus, lower failure stress and strain than $\pm45^{\circ}$ off axis laminate tensile shear test. This test is also very sensitive to small miss-orientation error and can not be applied to multiply oriented plies nor to randomly oriented chopped fibre composites.

Another test is cross-beam sandwich shear test. Petit [16] used this method for comparing the results of $\pm45^{\circ}$ off axis test and found good agreement within the allowable limit for design. Laminates commonly used for this test are $[0/90^{\circ}]_s$ or $[\pm45^{\circ}]_s$.

Duggan et.al. [19] predicted the actual state of stress in the test region and their analysis of $[\pm 45^{\circ}]_{s}$ revealed significant normal stresses
resulting in errors of 13 to 20% in shear strength which they attributed to corner effects. Fibre orientation and core reinforcement significantly influence the stress distribution present in the test section. Cross-beam sandwich test induces stress concentrations within the test section and at the corners. Also specimens used are complicated to fabricate and require large amount of material.

The plate twist method has been studied by Whitney [20] and Rothman et. al. [21], the latter used this method for shear characterizing carbon/epoxy composite. Theoretically the deflected surface of the plate is hyperbolic paraboloid derived on the basis of uniform twisting moments acting along the edges. Also in plate twist test, the applied point loads produce local bending moments that would add to the deflections due to twisting and result in lower apparent shear modulus. Split ring shear test and Short beam shear test are the other test methods. The plate twist and split ring shear test measure only shear modulus while the short-beam test measures shear strength [3]. Short-beam test does not produce reproducible results and the shear distribution depends upon the length to thickness ratio [22]. Mode of failure has to be carefully studied before accepting the failure shear stress for the split ring shear test.

Duggan et. al. [19, 23] proposed a slotted tension test for determining the in-plane shear properties. Tensile and

compressive stresses are provided by applying axial and transverse loads in ratio governed by the specimen width and distance between slots. Their analysis indicated that a shear stress concentration exists near the edge of compression pad; however, the error is less than cross-beam sandwich specimens. It is also reported that the test give good results for $[\pm 45^{\circ}]_S$ specimens, but found that when a $[0/90^{\circ}]_S$ laminate was tested the material failed in tension. Also the specimen preparation is not simple and the loading assembly is complicated.

Shear test methods employing some version of a double edge notched test specimen have been in use for many years. These test technique include methods suggested by Arcan [24], Iosipescu [25], and Sleeptz et. al. [26]. All three of these test methods employ the same basic principle to obtain pure shear at the test region. Notches machined in the edges of the test specimen, produce a uniform shear stress distribution as opposed to the parabolic shear distribution which would be produced in a specimen without notches. They differ only in the methodology of applying load to the specimen.

Arcan test specimen is a circular disk with cut-outs, resulting in a small test zone in the central region. This test method when used with unidirectional composite oriented in the principal directions of the fixture, corresponds to Iosipescu shear test. The original shear specimen (Goldenberg et. al. [27]) has been modified to circular S shape so that the specimen could be applicable to both shear and other two dimensional stress states. A separation between the central part of the specimen and exterior circular fixture was also introduced for applications to composite

materials. Arcan [24] pointed out some disadvantage and limitations of the specimen that the induced principal stresses always have opposite signs; special grips are needed because of the circular shape of the specimen. Moreover, the composite specimen has to be glued with the testing fixture with the help of supporting tabs prior to testing.

Another very attractive test method which is relatively simple to conduct, employs small easily fabricated specimens and is capable of measuring both shear strength and stiffness, was proposed by Nicolae Iosipescu of Rumania in 1967 [25]. Details about Iosipescu test method, with working principle,it's importance, use for composite materials etc. are given under chapter 2.

Sleeptz et. al. [26] utilized a slightly modified loading scheme from that of Iosipescu test method and termed the test as 'Asymmetrical Four-point Bending (AFPB) Test '. While the modification permits easier specimen loading, the induced shear stress becomes a function of loading point location dimensions , a distinct disadvantage in comparison to Iosipescu configurations. The AFPB test uses Iosipescu specimens , however, the application of load to the specimen is through cylindrical rods which can cause crushing of the specimen edges. Doublers must be glued onto the faces of the specimen to alleviate the crushing forces.

1.4 SCOPE OF PRESENT WORK :

The current studies are an attempt to characterize shear behaviour of materials used in the composite lab, using Iosipescu shear test method. For this a shear testing fixture is to be

manufactured having a similar design to that of modified Wyoming fixture of Adams and Walrath [30]. The materials used are bi-directional glass (coarse and fine) woven clothes, chopped glass random mat, kevlar 49 and unidirectional carbon reinforced with epoxy. In the case of unidirectional materials (kevlar and carbon) both 0° and 90° specimens are tested for complete shear characterization. Also in the case of carbon, tests are conducted by varying fibre orientation from 0° to 90° in steps of 15°. An attempt is also made for determining the inplane shear (mode II) fracture toughness using the same testing fixture. The material chosen for investigation is randomly oriented short glass fibre reinforced epoxy resin.

Details concerning the testing fixture design, material fabrication, specimen geometry design and preparation are given in chapter 3. It also gives an account of testing procedures for both shear characterization and fracture toughness test. The shear behaviour of the present materials are discussed in Chapter 4. A brief literature review of inplane shear fracture toughness and analysis of the test for random glass/epoxy composite using Iosipescu test fixture are also included in Chapter 4. Finally, important conclusions and some suggestions for further work are discussed in chapter 5.

CHAPTER 2

BACKGROUND ON IOSIPESCU SHEAR TEST

2.1 INTRODUCTION

A variety of test methods exist for determining shear properties of flat composite specimens. However, all of these test methods possess some disadvantage making them less than ideal. Also these tests were originally proposed for isotropic materials and their use to composite materials are questionable due to material orthotropy. Extensive numerical and experimental studies on these test methods and comparing their results for shear characterization of composites, were started in early 1970 's. This lead our interest to the use of some version of a double edge-notched specimen, originally proposed by Iosipescu in 1967. The use of Iosipescu test method for composite materials was started in 1977. Since then, a number of composite researchers have used this test and studied its suitability for complete shear characterization of composite materials.

2.2 IOSIPESCU TEST

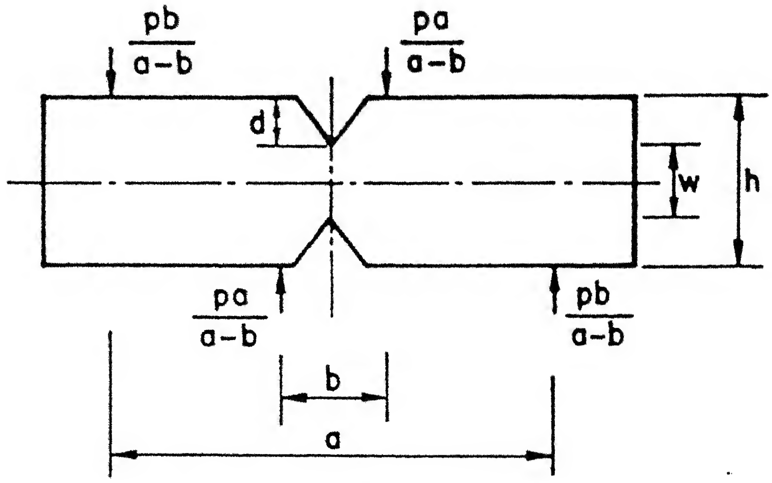
The Iosipescu shear test achieves a state of pure shear stress at specimen mid-length by applying two counter-acting moments produced by force couples. The Fig. 2.1a shows the Iosipescu specimen with force couples. For a total force P, as measured by the external testing machine, the applied forces are, as shown, calculated from equilibrium requirements, where 'a' is the distance

between the forces of the outermost couple and 'b' is the distance between forces of innermost force couple. A state of constant shear loading, as shown in the shear force diagram of Fig. 2.1b,is induced through the middle section of the test specimen. This shear force is equal in magnitude to the total applied force 'P'. The moment diagram of Fig. 2.1c shows the induced moments exactly cancel at the mid-length of the test specimen, producing a pure shear loading at that location.

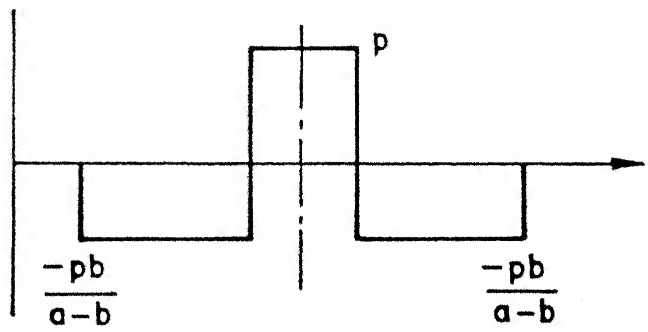
A loading fixture used for Iosipescu test is illustrated schematically in Fig 2.2. The end of the specimen is restrained from rotation by the loading fixture, while undergoing shear loading. This type of loading arrangement is found to be most suitable from the studies of Iosipescu. The load is applied along the edges of the specimen and only one half of the loading arrangement has to move, relative to the other half, during shear loading of the specimen.

Also by employing 90° vee-notches at the top and bottom edges, leaving a net-section depth at the centerline of one-half of the overall depth , uniform pure shear state is obtained which is confirmed by Iosipescu's photoelastic study on Plexiglas models. The uniform stress state apparently results from the coincidence of the principal stress directions at $\pm 45^{\circ}$ to the specimen axis with the 90° notch angle in the region of zero bending stress. Iosipescu's investigation was confined to homogeneous, isotropic materials. There is no stress singularity at the notch root because of the absence of normal stresses at that point.

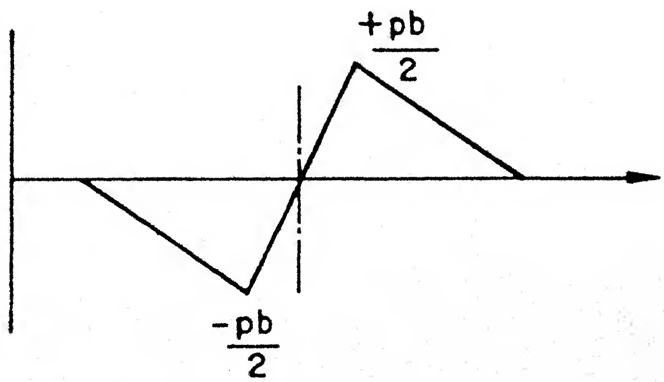
Iosipescu shear test method was first used by Adams and Walrath at the University Of Wyoming in 1977 to test three dimensionally reinforced carbon-carbon composite [28]. Subsequently



(a) Force diagram



(b) Shear force diagram



(c) Moment diagram

Fig.2.1 The antisymmetric loading of an Iosipescu specimen

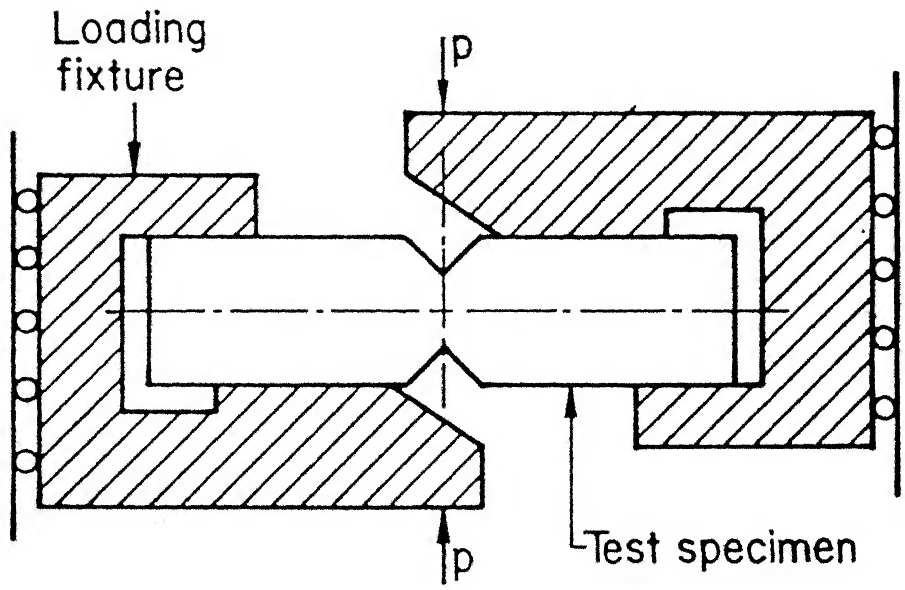


Fig.2.2 Schematic of the loading fixture for Iosipescu shear test

they have used this test method for a wide variety of composite materials ranging from unidirectionally reinforced glass/epoxy and graphite/epoxy to chopped glass fibre reinforced polyester sheet moulding components (SMC) and even materials such as wood and foam. Many of these results are presented in Ref. [3,4,29,30] and include shear fatigue as well as shear static data. In all of these applications , the method has worked well, resulting in apparent shear failures and very reproducible results. This test method is not limited to inplane shear response and can be used to determine interlaminar shear properties and would also be useful for measuring the strength of adhesive joints.

Adams and Walrath [30] performed a detailed finite element analysis for various specimen geometry parameters (notch angle, notch depth, notch root radius.) and obtained their influence on test results. They have also modified the earlier version of iosipescu testing fixture. In the modified fixture the loading points were moved away from the center-line of the specimen and used adjustable specimen support points. Finite element analyses carried out by Sleeptz et. al. [26] confirmed uniform stress distribution in isotropic material. However, in the case of composite materials, the stress distribution deviates from that of ideal conditions and also depends on material orthotropy. There is a significant stress concentration found at the notch root in unidirectional laminates. This is expected due to the shear coupling deformations along the notch flank which imposes a redistribution of stresses at the notch section, resulting in a stress concentration at the root. Bergner [31] suggested that suitably bonding doublers to the corners and rounding the notch tips can reduce the stress concentrations in

critical areas.

Only very few studies have been done to compare the results obtained by the iosipescu shear test with other shear test methods. Adams and Walrath [4] used SMC composite materials to compare the shear strength results from Iosipescu and short beam test methods. They concluded that the moduli values of various SMC materials obtained from Iosipescu tests agree well with the values obtained by other test methods. But the shear strength results obtained with the Iosipescu shear test of SMC materials were some what higher than those obtained with rail shear test. Swanson et. al. [32] conducted a comparison test on carbon-epoxy (AS4/3501-6) composite by torsion and iosipescu shear test and the results were found to agree quite well. Average initial modulus values differ by 1%, failure stress by 5% and failure strain by 31%. Sullivan et. al. [33] employed a combined experimental-numerical approach utilizing photoelasticity and finite element analysis. They compared the results of asymmetric four-point bend (AFPB)test method with the initial version of Iosipescu specimen geometry and testing fixture employed by Adams and Walrath. It was found that the AFPB method yielded more reliable shear modulus data, however, only isotropic materials were analyzed. Similar studies were performed by Spiegl et. al. [34] for quasi isotropic graphite/epoxy laminate. They concluded that changes in the notch geometry (depth, notch root radius, notch angle etc.) aimed at improving the stress distribution resulted in unexpected changes in the failure mode.

Lee and Munro [5] used a decision analysis technique to suggest most promising shear characterization methods. Based on a

set of eleven criteria ranging from accuracy and reproducibility of strength and stiffness parameter determination to ease of specimen preparation and testing , they suggested the 10° off axis tensile test, ±45° laminate test and the iosipescu shear test as the most suitable tests for inplane shear characterization of composites. A combined experimental-analytical study for accurate determination of shear modulus and strength of unidirectional composite using the off axis (10° and ±45°) tension test and iosipescu shear test by Pindera et. al. [35] recommended 45° off axis test for shear modulus and the 0° Iosipescu specimens for determining an upper lower bound of the shear strength. They also concluded that the shear stress distribution is more uniform in the test section for 90° specimens than 0° Iosipescu specimens.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 TESTING FIXTURE :

Iosipescu proposed this test in 1967 and used for characterizing isotropic materials in shear. Use of this test for composite materials was started in 1977 by Adams and Walrath [3,4,30] of University of Wyoming. They used a scaled-down version obtained from Place [3]. Since then they were using Iosipescu shear test method for a wide variety of materials and performed a detailed analytical investigation on stress distributions for orthotropic materials. These studies lead to the improvement in the design of original Wyoming fixture [29]. Adams and Walrath redesigned it in the early 1980's and complete details of the design including complete part drawings were obtained from Ref. [30]. In the modified version of fixture, the loading points were moved away from the notch root to minimize the intrusion of loading point induced normal and transverse compressive stresses into the test region. By incorporating adjustable clamping mechanisms, using wedges and thumbwheels, they minimized the rotation of specimen during testing caused by loose fit between test specimen and fixture. Such fixture can accommodate a variation in specimen height of as much as 1 mm. This modification also made specimen preparation simple and less expensive. Also the overall size of the fixture was changed to accommodate specimens of 75 mm long, 19 mm width and can be of any thickness upto 13 mm, i.e., 50 % more in size than the early specimens.

The fixture design used for current investigation is exactly similar to the Modified Wyoming fixture. The complete design and drawings obtained from ref. [30] have all dimensions in inches and American standards for threads. Therefore; while changing the dimensions to millimeter, there is a slight increase in the overall dimensions. Indian or British thread standards have been followed for convenience. Thus the newly developed fixture can accommodate specimens of length 76 ± 6 mm, height 19.5 ± 1 mm and can be of any thickness upto 13 mm.

All parts of the fixture were fabricated from EN-24 steel (carbon percentage 0.4 and BHN 220(B)) with the exception of the linear bushing and post. The post is made of Silver steel which is a high carbon steel with carbon percentage between 0.6 0.65%. The sleeve bushing is made of brass. The 'T' shaped alignment tool is made of 4 mm dia. Silver steel rod. All parts were made by milling machines with the exception of bushing. Bushings and bore of right half fixture mounting block were made in a lathe. The assembled fixture with the loading arrangement is shown by photograph in Fig. 3.1 The part drawings of the testing fixture are included as Fig. 3.2 through 3.6.

The entire front face of the specimen remains visible during testing in the current fixture. The specimen may be installed directly from the front. Failure progression can be monitored visually. The left half of the fixture is now fixed to the base. Only one half of the fixture is to be moved to apply the shear loading. The two fixture halves are identical but one half is rigidly attached to the base plate by means of a spacer block, which is a 'L' shaped mounting bracket. The other half moves up and down

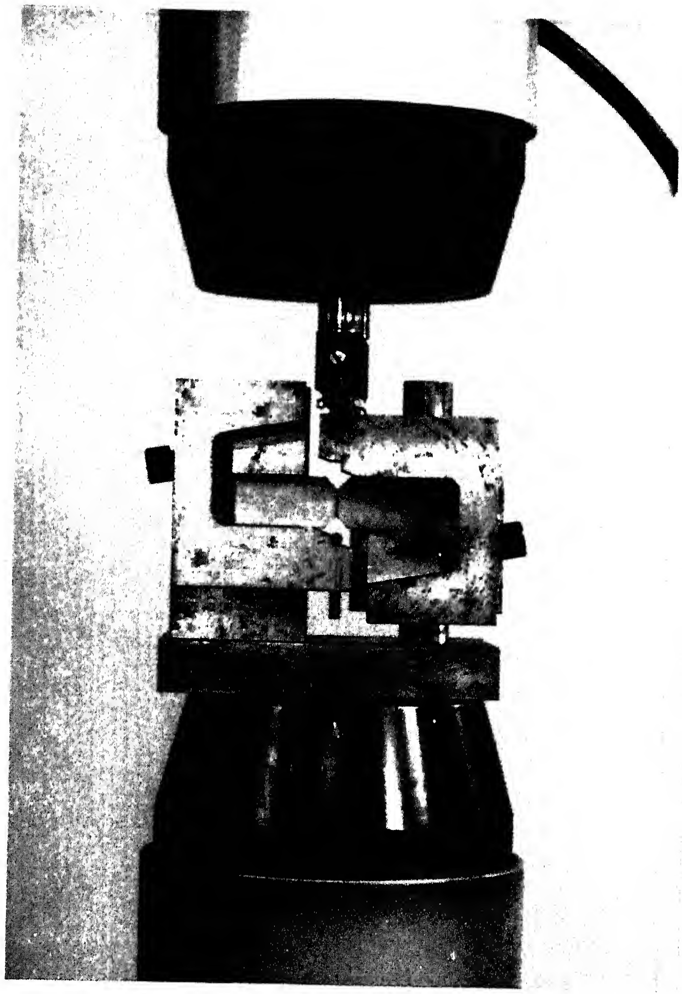


FIG. 3.1 IOSIPESCU TEST FIXTURE PLACED BETWEEN THE LOADING POINTS.

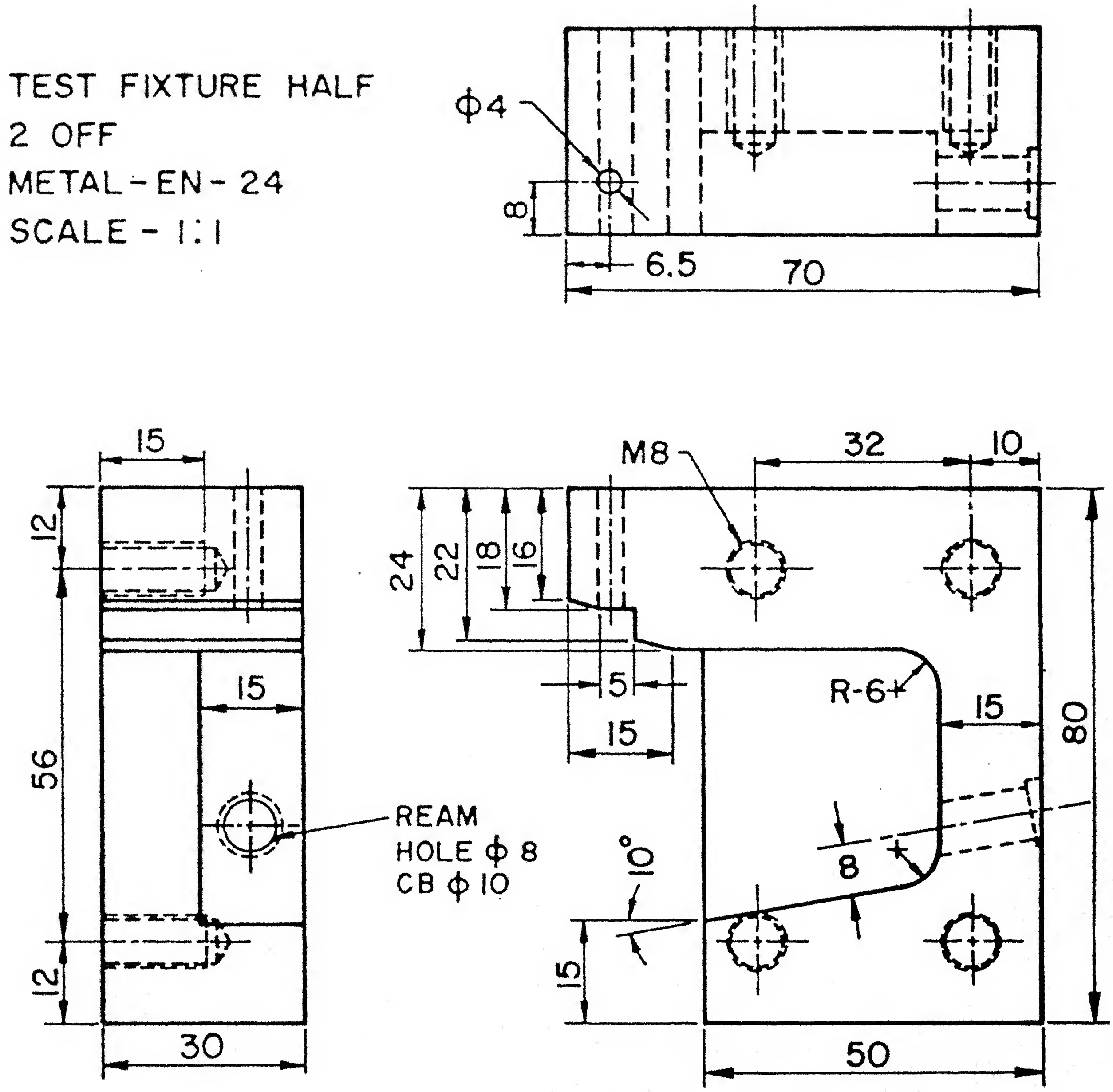


Fig. 3.2 Iosipescu shear test fixture half

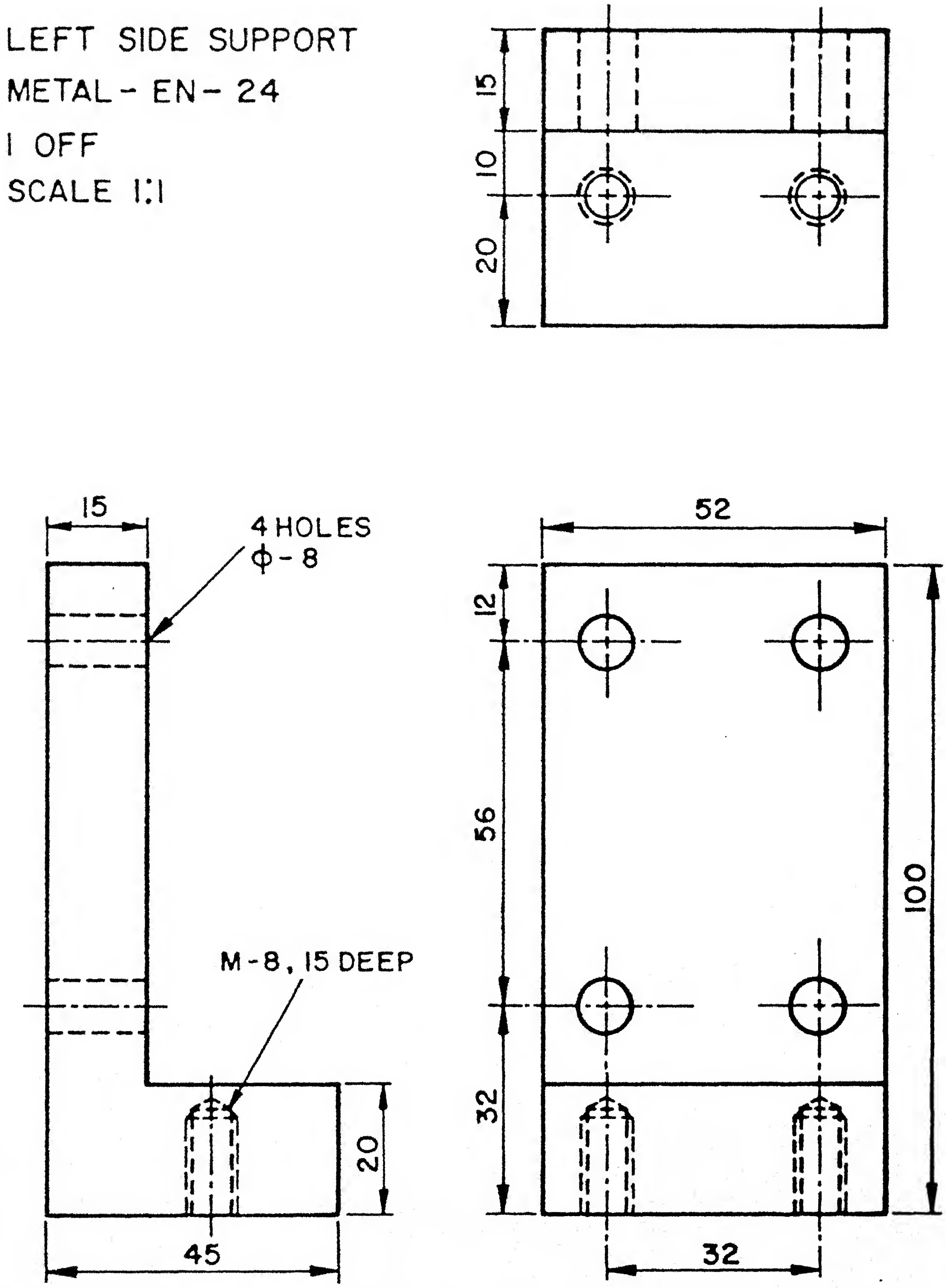


Fig. 3.3 Iosipescu shear test fixture fixed half left mounting bracket

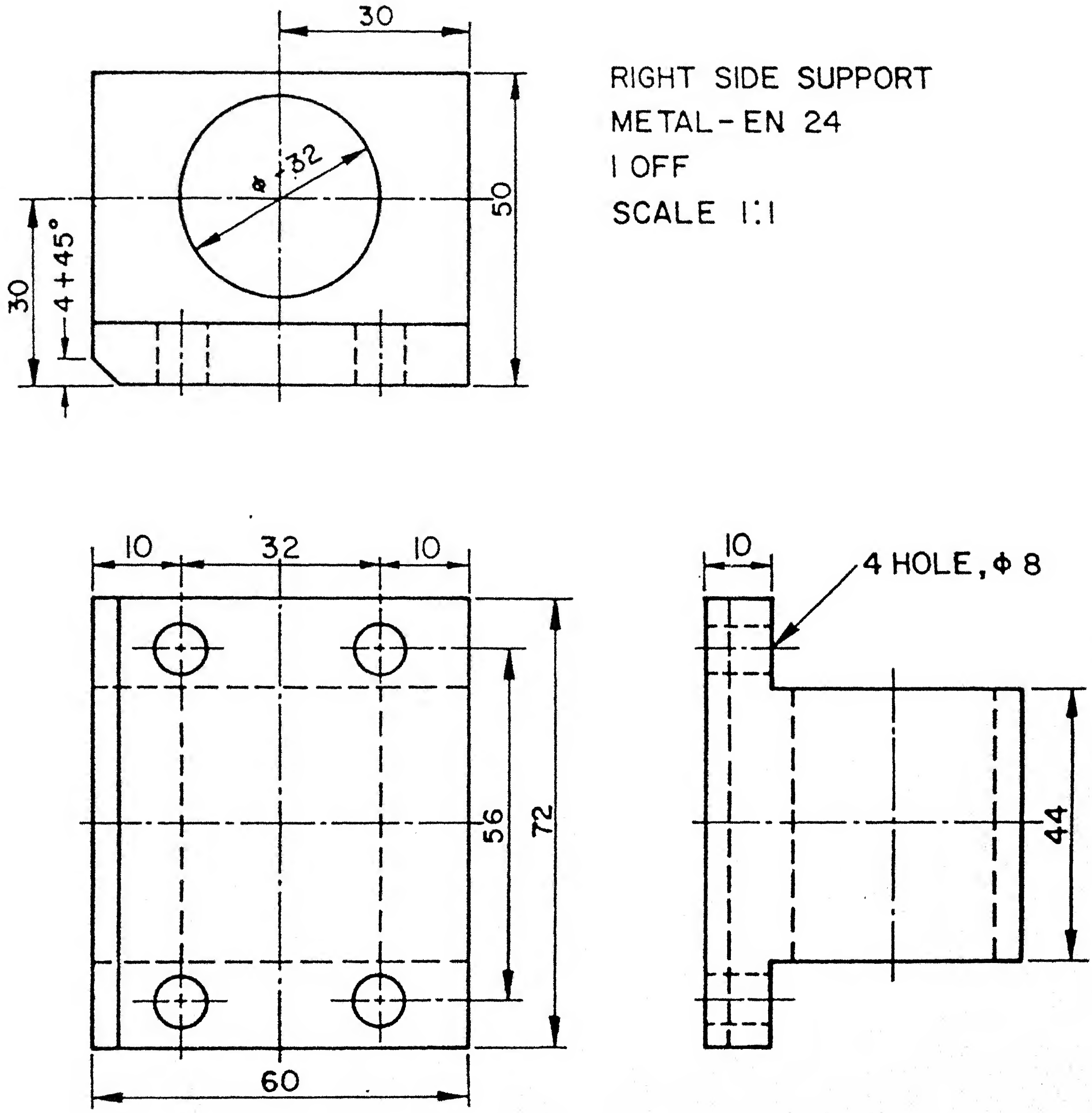


Fig. 3.4 Iosipescu shear test fixture bearing mounting assembly

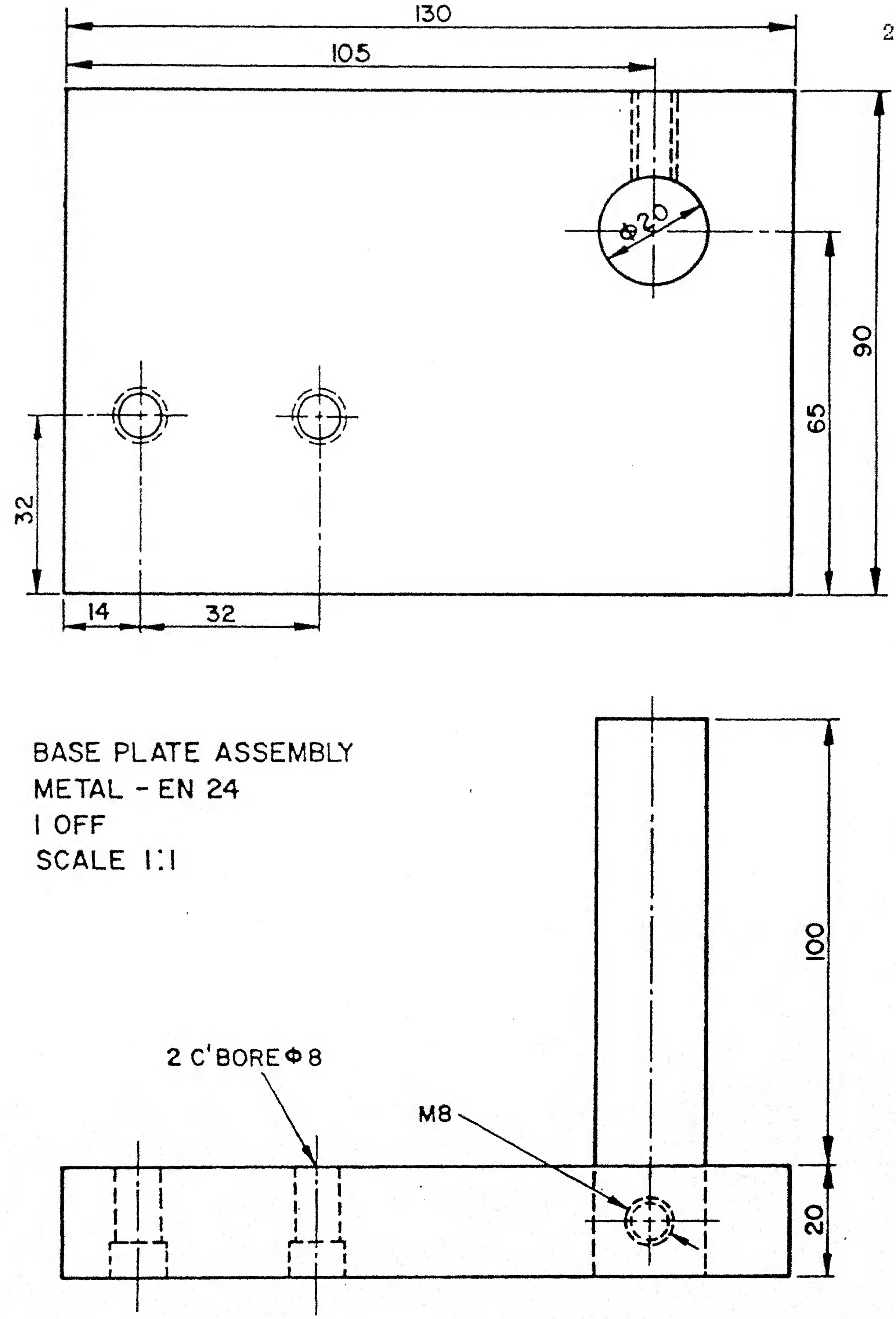


Fig. 3.5 Iosipescu shear test fixture base and post assembly

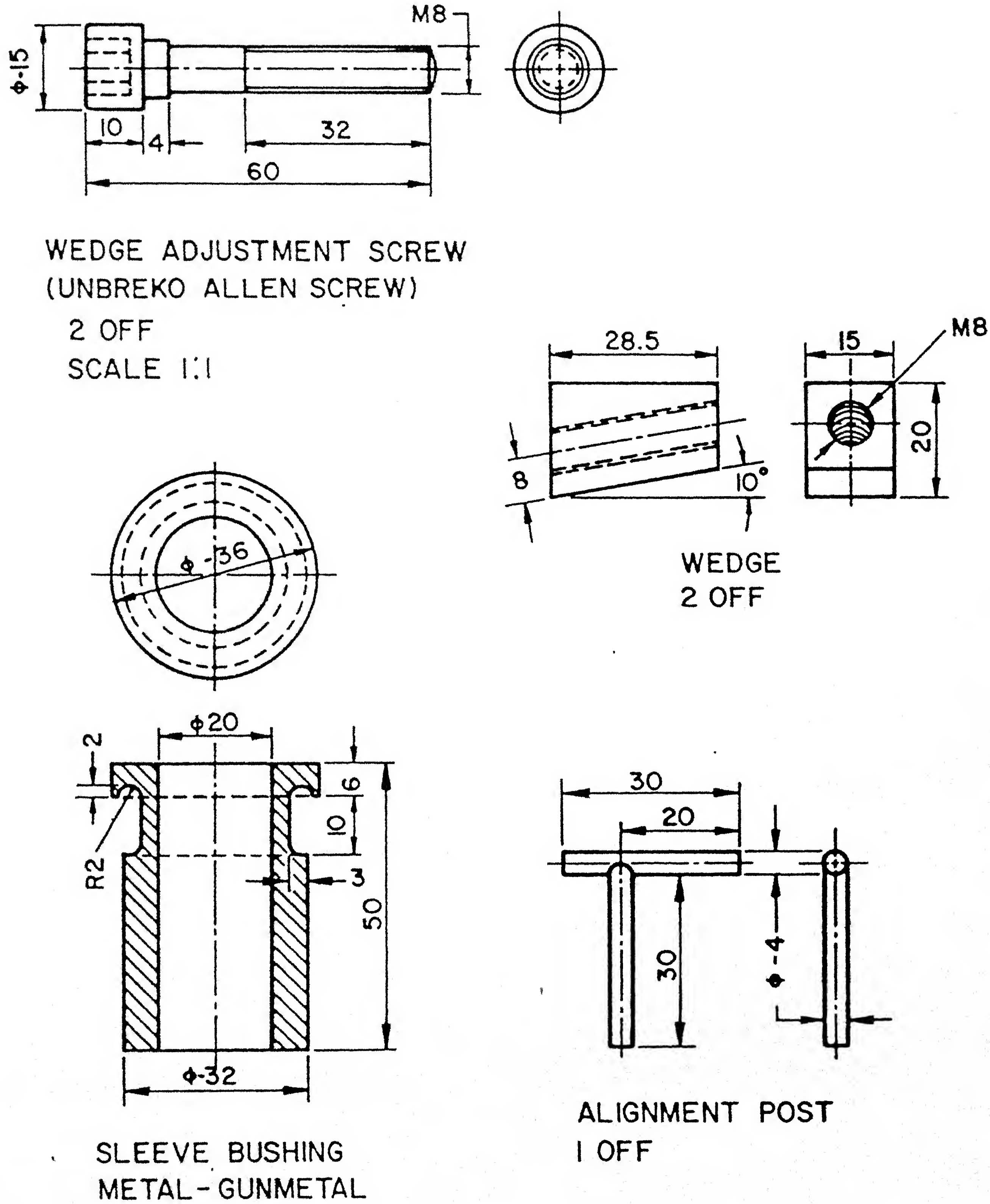


Fig.3.6 Iosipescu test fixture clamp assembly, sleeve bushing and alignment post

on a post which is attached to the base plate. The right half of the fixture is attached to a bearing mounting assembly . The bearing mounting assembly slides on the post with a brass sleeve bushing. The bushing is so fabricated that the fit between post and bushing is tight enough to minimize the amount of play in the fixture. The specimen centering guide is now built into the left lower half of the fixture. The alignment guide can be lifted up with one finger to index into the lower notch of the specimen while installation. It then drops back out of the way into a recessed position when released.

The loading points in this fixture is further away from the center line from that of modified Wyoming fixture, i.e.,8.5 mm from the test section. Further modifications were to be done due to problems encountered in testing Kevlar material. Since the deformation of Kevlar was pronounced, the portion of fixture half projecting beyond the loading point, established contact with the adjacent top lands of notches. On further loading the contacts points were getting crushed and strength tests could not be continued. Thus for providing space for considerable deformation, the depth of alignment guide recess was increased. After this modification the testing fixture worked satisfactorily for the complete shear characterization of all types of materials used.

3.2 MATERIALS USED :

For the present study a wide variety of materials were selected. In fact an attempt was made to shear characterize all the materials available in the composite materials lab. Composite

materials were fabricated using Kevlar 49, carbon unidirectional fabric and three types of glass reinforcements. The Kevlar fabric used has unequal counts and denier, in warp and fill directions and is generally referred to as the unidirectional weave and the fibre volume fraction in warp and fill direction is 10:1. In this study, warp direction is the longitudinal or 0° direction and fill direction is transverse or 90° direction. Carbon fabric is unidirectional with carbon in the warp direction and E glass of low count and denier in the fill direction. In the case of E glass, chopped random mat and two types of bi-directional fabrics were used. The bi-directional fabrics have balanced weave in the warp and fill directions but one is coarse woven (low count) and the other is fine woven (high count). The chopped random mat is isotropic in plane and uses short E glass fibres of approximate length 50 mm for reinforcement.

The specifications of these materials, as supplied by the manufacturers are given in Table3.1 All these materials were compatible with the epoxy resin Araldite LY 556 cured with 10% by weight of hardener HY 951. In the case of kevlar the fabric was pre-treated by the manufacturer with a coupling agent for epoxy compatibility. The properties of epoxy resin, as supplied by the manufacturer, are given in Table 3.2 Thus almost all types of reinforcements available were used for shear characterization. A detailed study was performed on carbon/epoxy composites with different fibre orientations with respect to loading axis. Fracture toughness studies in shear mode was performed using chopped random glass/epoxy composite.

MATERIAL		E - GLASS		KEVLAR 49	CARBON
1. TYPE/CODE	-	F/6/22	FPE	CS STYLE 343	GRAFIL 150 G/E
2. WEAVE	Coarse, open weave, balanced, plied yarn.	Fine, plain weave balanced, single yarn.	Chopped random mat	Crow foot CS 805	-
3. SUPPLIER	Swan Co. India	Mantex glass fiber Ind. Limited	Fiber glass Pilkington Limited	Dupont, USA.	Courtlauds, England.
4. COST	160 Rs/kg.	40 Rs/m^2	-	300 Rs/Yard	60 Rs/m
5. DENSITY gm/cm^3	2.54	2.54	2.54	1.44	1.85
6. AREA DENSITY gm/cm^2	390	180	600	190	340
7. Thickness of plate -mm	0.15	0.075	0.3	0.1	0.18
8. Modulus GPa (Specific Modulus)	72.4 (28.5)	72.4 (28.5)	72.4 (28.5)	130 (87)	210 (113.5)
9. STRENGTH GPa (Specific strength)	3.5 (1.38)	3.5 (1.38)	3.5 (1.38)	2.8 (1.87)	2.4 (1.3)

Table 3.1 SPECIFICATIONS OF MATERIALS USED

PRODUCT	- CIBA Geigy India Ltd.
CATEGORY	
RESIN	- ARALDITE LY 556
HARDENER	- HARDENER HY 951 (10% OF Araldite by weight)
Mixing	- At room temperature
Viscosity, CP	- 5000 - 8000
Pot life, hr.	- 0.5 - 1.0
Specific Gravity	- 1.2 - 1.3
Tensile Modulus, MPa	- 2800 - 4200
Tensile Strength, MPa	- 55 - 130

TABLE 3.2 SPECIFICATIONS OF EPOXY RESIN USED

3.3 MATERIAL FABRICATION :

Composite laminate plates were cast by hand lay-up technique. The fabric or mat were cut to required size. The size of cloth was kept such that a good center portion of 320 x 200 mm size could be obtained. The edges of the clothes were dressed properly and dust etc. were removed. In case of Kevlar, the fabric was demoisturised by heating it in an oven at 105 $^{\circ}$C for sixteen hours and cooled in the oven to room temperature. This is to avoid any moisture regain prior to processing. Epoxy resin (Araldite LY 556) was preheated to about 100 $^{\circ}$C for about an hour to remove absorbed moisture. The resin was then allowed to cool to room temperature (23 $^{\circ}$C) in air.

Composite plates were cast by hand-lay-up technique between two 25 mm thick M.S. Plates. The M.S. plates were nickel coated on one side and affixed with heating element on the other. A mylar sheet was placed on the lower mould plate. The resin and hardener were thoroughly mixed. The amount of hardener was 10 % of epoxy used. A layer of resin was spread over the mylar sheet and the first fabric layer was placed. Epoxy was applied over the fabric by means of a brush. This process was repeated till all the fabric layers were placed. To enhance wetting and impregnation, after the second layer, a teethed steel roller was used to roll over the fabric before applying epoxy resin. Also the resin was tapped and dabbed with spatula before spreading resin over fabric pieces. Another mylar sheet was placed over the top most layer. Steel spacers of 3 mm thickness were placed at all four corners between the two mylar sheets. A rubber roller was rolled over the top sheet

to squeeze out excess epoxy and entrapped air. The upper mould plate was then placed in position. The mould plates were connected by uniform tightening of nuts on the bolts provided at the four corners.

The laminate thus prepared was cured for 6 hours at room temperature followed by 12 hours at 55 -60 °C. The heating was done through several 250 W heating elements placed on the outer surface of each mould plates. The rate of heating could be controlled through a variac. After curing, the composite plate along with mylar sheet was removed. The mylar sheets were then removed to get a fine finished composite plate.

For glass/epoxy composites fibre volume fraction can be found by resin-burn of test. But for Kevlar and carbon composites resin burn-off test fails as the fibres also burn off. Other methods like dissolving the matrix in solvents etc. are tricky, therefore, volume fraction of fibres in the laminates for all materials were calculated from the mass of fabric in composite as follows:

$$V_f = (A\ N\ \rho_{fa} / \rho_f) / (A\ t)$$

$$= N\ \rho_{fa} / t\ \rho_f \qquad - \quad 3.1$$

Where,

V_f : fibre Volume fraction

A : Area of the composite laminate - m^2

N : Number of fabric layers in the laminate

ρ_{fa} : Areal density of fabric - Kg/m^2

ρ_f : Density of fibre - Kg/m^3

t : Thickness of the laminate - 3×10^{-3} m

The amount of epoxy used, number of layers of fabric and volume fraction from formula 3.1 as well as from resin burn-off tests are given in Table3.3.

In all the cases the volume fraction of fibres is kept around 55 % and thickness of plate 3 mm. Thus the number of layers of fabric in each case was calculated from the modified relation 3.1 as shown below;

$$N = V_f \; t \; \rho_f \; / \; \rho_{fa} \qquad - \qquad 3.2$$

$$= 0.165 \; \rho_f \; / \; \rho_{fa}$$

3.4 SPECIMEN DESIGN AND PREPARATION :

The specimen used for shear characterization was originally proposed by Iosipescu [25]. Adams and Walrath [29,30] have done extensive experimental and numerical investigation with Iosipescu specimens. Their studies on different notch parameters like depth of notch, notch angle and notch root radius gives an insight to the effect of these parameters on stress distributions of Iosipescu specimens during testing. Their results and suggestions were useful for designing the specimens for accurate shear characterization. The specimens used have a 90° or 110° 'V' notches on top and bottom edges of the specimen at its mid-length (Fig. 3.7) Thus the test section of pure shear is the region between the two notch roots.

Iosipescu [25] has proposed an optimum notch depth of 22.5 % of overall depth for isotropic materials. Later the studies of Adams and Walrath [30] on orthotropic materials suggested that notch

MATERIAL	E - GLASS				KEVLAR 49	CARBON
1. Code used	Coarse glass	Fine glass	Random glass		K	C
2. Plate thickness (mm)	3	3	3	2	3	3
3. No. of layers used.	11	23	7	4	12	9
4. Amount of Epoxy used (gms.)	450	500	400	300	450	300
5. Volume fraction -%						
From eqn. 2.1	56.2	55.2	55.12	54.50	52.77	55.2
From burn-off test.	51.61	51.90	49.57	48.70	-	-

Table 3.3 SPECIFICATION OF COMPOSITE LAMINATES

depths between 20 % and 25 % of overall specimen height, should work satisfactorily. Moreover, their studies indicated that a 90° notch is most suitable angle for testing isotropic materials and notch root shear stress concentration is minimum. Increasing the notch angle was similar to decreasing the notch depth, i. e., shear stress at the notch root was reduced. But for orthotropic materials, notch angles of 110° or 120° may be more suitable for shear testing. This greater notch angle will reduce the shear stress concentration due to orthotropy. Increasing the notch root radius, significantly reduced the notch root shear stress concentration. But it also shifts the point of maximum shear towards the nearest loading point. They suggested notch root radius between 0.64 mm and 1.37 mm for Iosipescu shear test specimens. To avoid buckling during testing, a minimum specimen thickness of 2.5 mm should be used [29].

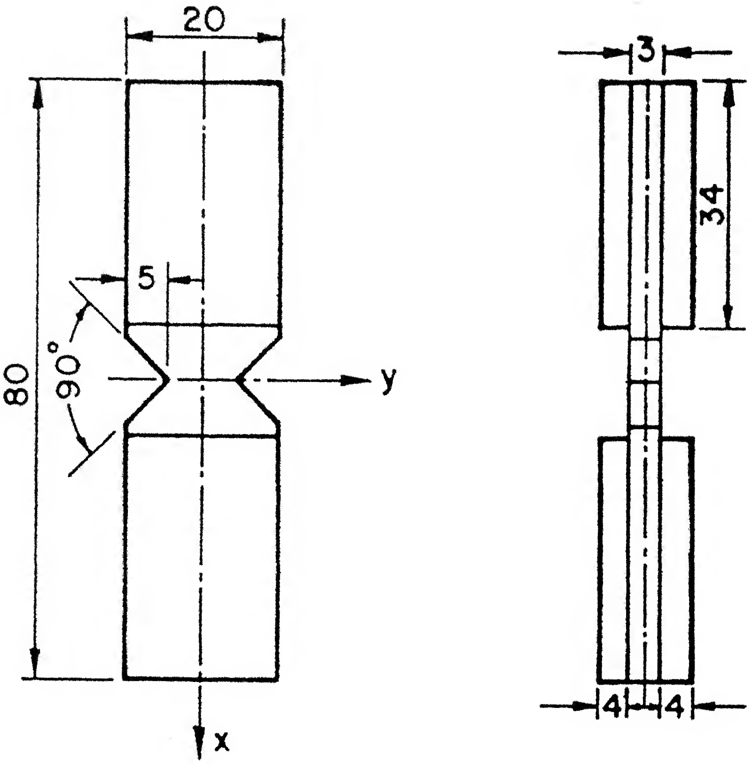
For the present studies, the specimens used for Iosipescu shear tests were 80mm long, 20 mm height with an "as received" thickness of 3 mm. For fully characterizing the present materials, static tensile tests were also performed in-addition to Iosipescu test. The tensile specimens were made from the same laminate as that of Iosipescu specimens. The specimens used were 180 mm long, 20 mm in width and approximately 3 mm thickness. Specimen preparation of these tests involves, cutting the laminates to required size and finishing them. In the case of Iosipescu specimens 90°/110° Vee-notches were made on top and bottom edges at specimen mid-length, notches were finished and end tabs were fixed.

Cutting of glass/epoxy and carbon/epoxy composites laminates were relatively simple as they can be easily cut using a diamond impregnated wheel, cooled by running water. The cutting

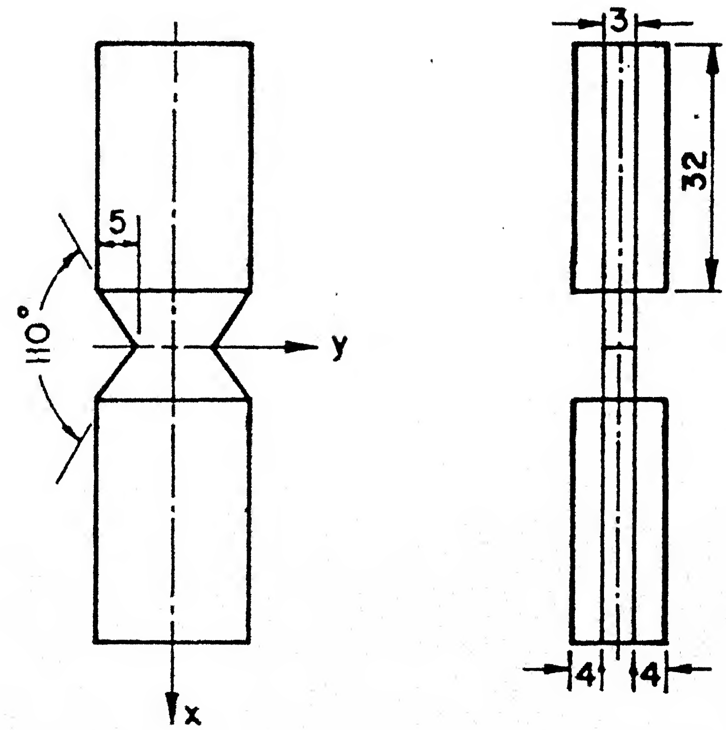
speeds were moderate and good edge surface finish were obtained. But for Kevlar 49 many of the traditional machining techniques are not suitable. The best results in cutting laminates were obtained through a circular saw, when unconventional side (slant side of teeth) of a metal slitting fine teethed HSS cutter was used, at high speeds with water as coolant. Cutter size used was 150 mm. in dia. and 0.8 mm thickness with 3 teeth per cm. Cutter speed used was about 30 m/s. The cutting speed was quite high in dense fibre direction (cutting less fibres) and moderate in cross direction. The quality of the edge was quite good except for few broomed fibres at one side of edge from which the cutter comes out after cutting. The brooming was easily removed by abrading the edges on simple wood sand paper.

All the specimens were finished by abrading the edges on a fine Carborundum (C - 100) paper. The notches were cut in the All Cut machine (initially to a depth of 20 % of overall specimen height) with a fine teethed blade at medium speed. The notches were then finished using a special hardened single edged blade by hand and the notch roots were made sharp. The random glass/epoxy composite used is isotropic in plane and the two bi-directional glass\epoxy composites have an orthotropy ratio equal to one. Thus for these materials 90° notches were used. (Fig. 3.7a) The Kevlar/epoxy and carbon/epoxy composites used were unidirectional with orthotropy ratio more than one. Therefore, specimens of both 0° and 90° fibre orientation with respect to loading axis were made and 110° notches were used for these materials. (Fig. 3.7b)

While these specimens were tested, edges of the specimen



(a) Specimen of notch angle = 90°



(b) Specimen of notch angle = 110°

Fig.3.7 Iosipescu shear test specimen

coming in contact with the fixture were getting crushed. Thus the shear strength tests were unable to continue till the failure of specimen at test section. Adams and Walrath [30] have reported edge crushing problems and suggested many solutions to alleviate the edge crushing; i. e., by increasing the notch depth, reinforcing ends of specimen to withstand higher compressive loads,using $[0^{\circ}/90^{\circ}]_S$ lay-up laminates etc. and these would not alter the shear response of the material much.

Thus to prevent edge crushing notch depths was increased from 20 % to 25 % of overall specimen height and tabs were used at the ends. Initially tabs used were of length 31.5 mm (which is the distance between the end of specimen to the inner loading point when specimen was aligned in the fixture), 20 mm in width (same as that of specimen) and of thickness 3 mm. But these specimens were also subjected to crushing at the inner loading point regions. Eventhough it was not major, it was undesirable. After some trial and error, a suitable tab dimensions of 34 x 20 x 4 mm was found working satisfactorily. Coarse cloth glass composite of about 50 % volume fraction of fibres (14 layers of fabric were used to make laminate of 4 mm thickness) was used for making tab. The tabs were cut and finished to required size and are fixed to the specimen ends using Fevicol CYN 702 adhesive. It is a cynoacrylate adhesive with set time of 20 sec. In each case two tests were conducted for modulus and three tests were performed for shear strength.

Shear mode fracture toughness tests were performed using chopped random glass/epoxy composites of approximately 55 % volume fraction of fibres. The specimens were made [illegible] mm laminate plates and finished to the size of 80 x 2[illegible] [illegible] earlier.

The notches (slit cracks) were machined at the specimen mid-length using a high speed steel cutter of 0.2 mm thickness. A lathe suitably modified was used for this purpose. Tabs used were of size 36 x 20 x 4 mm, made of glass/epoxy as mentioned above. These were glued to the specimen using Fevicol CYN 702. Figure 3.8 shows a fracture toughness specimen. The initial half crack length 'a_0' was varied from 2mm to 8 mm.

3.5 TESTING PROCEDURE :

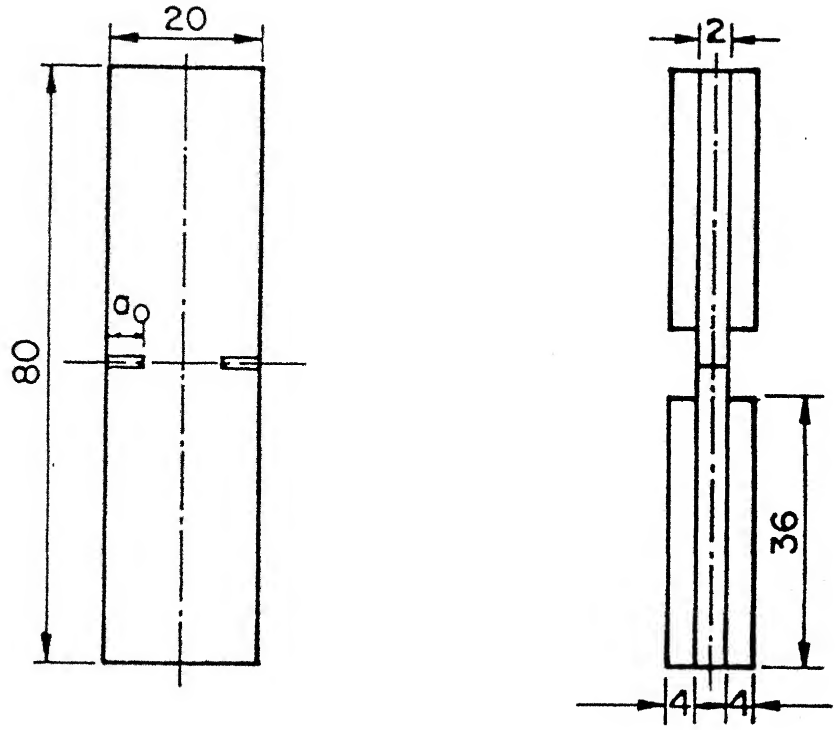
For fully characterizing the materials, static tensile tests were performed for all materials along with Iosipescu shear tests. All tests were performed on an MTS servo-hydraulic testing machine of capacity ± 10 tonnes. In this thesis it is useful to define three coincident reference frames (rectangular right-hand coordinate system) X-Y, L-T and 1-2 to avoid confusion.

1) X-Y coordinate system with 'Y' axis parallel to the loading direction and 'X' axis perpendicular to it.

2) L-T coordinate system for principal material directions with 'L' denoting longitudinal or parallel to the fibre direction and 'T' as transverse or perpendicular to fibres.

3) 1-2 coordinate system for principal stress directions along which the strain gauges are mounted.

In the case of bi-directionally reinforced composites 'L' and 'T' can be any one of the fibre directions and for Randomly oriented fibrous composites, the choice of principal material directions are arbitrary as it is isotropic in plane.



a_o - Initial half crack length

Fig. 3.8 Fracture toughness specimen

For static tensile tests, the specimens were secured between the grips. A small try square was used to align the specimens in vertical position. The grip was of wedge shape with serrated surface for holding the specimen. The tests were conducted in load control, at a loading rate of 16.35 N/s., and for measuring strains extensometer or strain gauges were used. MTS extensometer of 25 mm gauge length was mounted at the gauge section and while loading, load-strain curve was plotted using Ominograph plotter. The strain gauge tests were performed with one gauge along the loading direction and other perpendicular to the loading direction. The strain gauges used were SR-4;AF-7 gauges of 120 Ω resistance with gauge factor 1.84 and of gauge length 6 mm. They were mounted on either side of the specimen at gauge section using Fevicol CYN 702. Tests were performed with fibre direction along the loading axis for longitudinal modulus 'E_L' and poisson ratio 'v_{LT}' and fibre direction perpendicular to the loading line for transverse modulus 'E_T' and poisson ratio 'v_{TL}'.

Iosipescu shear tests were performed with the test fixture designed to be used in a testing machine set-up in compression mode. The fixture is placed between the loading points with the base plate resting on the lower compression pad of the testing machine and the load is applied on top of the right half of is the fixture. The loading is done using the center loading point of three point bend test apparatus. The load is applied along a line over the whole thickness of right half of the fixture. The specimen is so placed in the fixture that the loading point falls exactly over the specimen notch root. Fig. 3.9 shows the photograph of the experimental arrangement with the fixture placed between the loading points in

MTS system.

Shear modulus tests were performed in load control and can load the specimen upto 10 % of maximum capacity. The loads could be directly read from the digital display. For measuring strains, two strain gauges were fixed along the principal stress directions which are $\pm 45^\circ$ to the longitudinal axis of 0° specimen and were centered between notches. The strain gauges used were SR-4; a-8 gauges of 120 Ω resistance with gauge factor 1.84 and of gauge length 4 mm. They were mounted on either side of the specimen using Fevicol CYN 702 adhesive. The strains were measured using strain indicators. For this two Measurements Group's digital strain indicator (Model P-350) of range ± 50000 microstrains and accuracy ± 1 % of reading; were used. Initial readings were taken with no load on the specimen, the strain indicators knobs were adjusted to balance the quarter bridge. The load was increased in steps of 10 kg. by adjusting the knob provided in the testing machine and on each steps strain readings were noted after balancing the strain indicator. From these readings, strains for each load can be calculated.

The Fig. 3.10 shows a free body diagram of specimen at gauge section. Fibres are oriented at an angle 'θ' from the X axis. The convention used here is in a 0° specimen, L and X axes coincide where as in a 90° specimen, L and Y axes coincide. The applied load 'P' is negative as it is opposite in direction to that of Y axis (loading axis). The shear modulus 'G_{xy}' can be calculated from the relation

$$G_{xy} = \sigma_{xy} / \gamma_{xy} \qquad - \quad 3.3$$

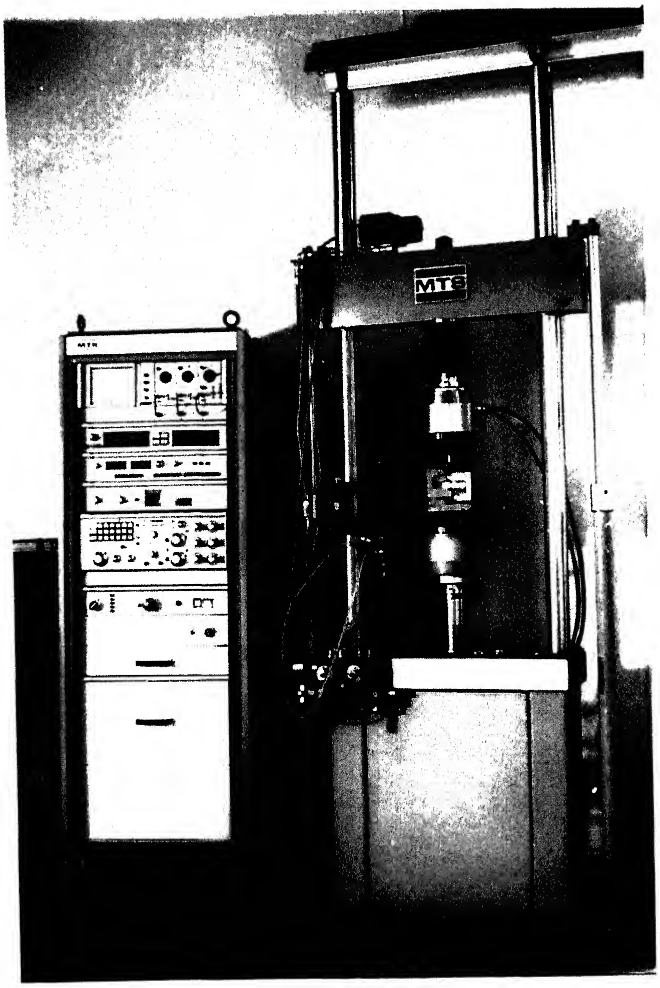


FIG. 3.9 EXPERIMENTAL ARRANGEMENT FOR IOSIPESCU TEST.

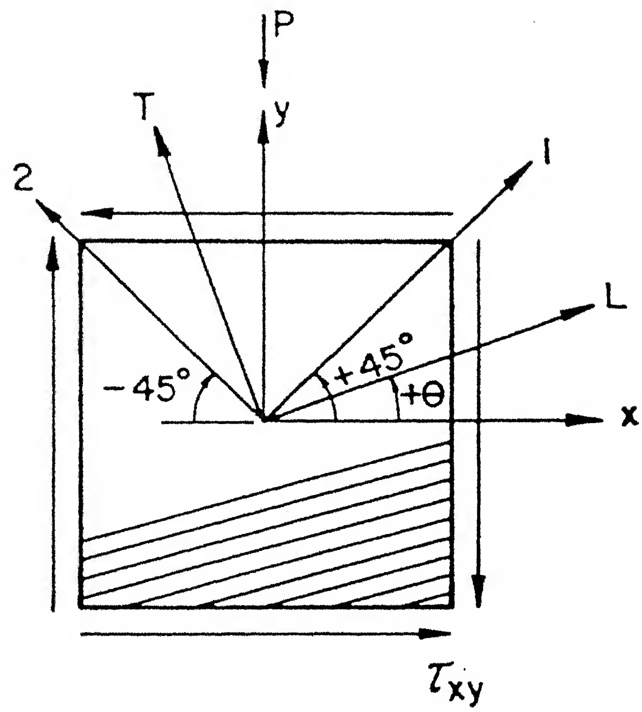


Fig.3.10 Free body diagram of specimen at test section

Where,

$$\sigma_{xy} = - P / w \times t \qquad - \qquad 3.4$$

$$\gamma_{xy} = \epsilon_{45} - \epsilon_{-45} \qquad - \qquad 3.5$$

Here,

w = the test section width

t = thickness of specimen

ϵ_{45} = strain measured along + 45° from X axis

ϵ_{-45} = strain measured along - 45° from X axis

In all the cases shear stress-strain graphs were plotted and the data were analyzed using PC/XT computer.

Shear strength tests were performed in load control and the testing system was set to load automatically at a rate of 16.35 N/s. Whole loading, load-deflection curve was plotted and the ultimate load 'P_{ul}' was noted for failure of the specimen. The ultimate shear strength 'σ_{ul}' was calculated using the relation

$$\sigma_{ul} = P_{ul} / w \times t \qquad - \qquad 3.6$$

Shear mode fracture toughness tests were also conducted in a similar manner. But the testing machine set-up was changed to apply compression in stroke control. The specimens were strained at a rate Ø.Ø82 mm/s. The stroke value was brought to zero position for zero load on the specimen and the X-Y recorder was positioned on the graph paper. The testing system was made to run automatically and load deflection curve was plotted in each case. The plots obtained were digitized using HP 747ØA a plotter and the digitized data were collected in PC/XT computer for further processing.

The 'J' integral was calculated using the method suggested by Early and Burns [49,50]. According to this method, the material property J_{IC} can be determined with two fracture specimens that differ only in crack area and from the load-displacement records by the equation

$$J_{IC} = 1 / \delta A \oint P \times dX \qquad - \qquad 3.7$$

Where,

δA = the finite difference in crack area.

$\oint P \times dX$ = the area between the two load-displacement curves corresponding to the specimens with finite difference in crack length.

CHAPTER 4

RESULTS, ANALYSIS AND DISCUSSION

Iosipescu shear test method, originally proposed for isotropic materials, has been used for composite materials recently. For composites, this test method is in a state of development. The suitability of this method for composite materials with different types of reinforcements have been investigated in the present studies. An Iosipescu shear test fixture used was fabricated . The reinforcements used were glass cloth with coarse weave and fine weave, randomly oriented short glass fibre mat, Kevlar cloth and unidirectional carbon fibres. The coarse glass cloth composite and fine glass cloth composite have bi-directional reinforcements with orthotropy ratio (E_L/E_T) equal to one while random glass composite was isotropic in the plane of loading. Kevlar composite and carbon composite were in the class of unidirectional composites with higher orthotropy ratios.

Composite laminates fabricated with the above reinforcements had approximately 55 % fibres by volume and an 'as received' thickness of 3 mm. Both Iosipescu shear test and static tensile test were conducted on all the materials considered in the present study. All these tests were performed on a 10 tonne MTS servo-hydraulic testing system (Model 810.22). The two tests together yielded all the four independent elastic constants, namely, the elastic moduli (E_L and E_T), Poissons ratio (ν_{LT}) and in-plane shear modulus (G_{LT}). Here the 'L' refers to the longitudinal or 0° direction and 'T' to transverse or 90° direction. Ultimate in-plane shear strength of the above mentioned materials were also determined

using Iosipescu test and the mode of fracture in each case has been carefully examined.

Iosipescu shear tests were conducted on carbon-composites with fibre orientation as a variable with respect to the loading axis. The shear modulus obtained from experiments were compared with the theoretically calculated values using the four independent material properties in 'L' and 'T' directions. Use of Iosipescu shear test for determining the shear mode fracture toughness (Mode II) was examined using double edge notched (DEN) specimens made of random glass composite.

4.1 STATIC TENSILE BEHAVIOUR :

Static tensile behaviour of all materials was studied through uni-axial tension tests. These tests were conducted under load control. Strains were measured using extensometer as well as strain gauges. For unidirectional composites (Kevlar/epoxy and carbon/epoxy) longitudinal (L) and transverse (T) properties were determined through separate tests. In the case of glass/epoxy composites, the properties in 'L' and 'T' directions could be assumed to be same due to the types of reinforcement used. Thus, tests were conducted only in one direction and same values were assigned to other direction. The extensometer used has a gauge length of 25mm. Strain gauges used were of 6 mm gauge length and 120 Ohm resistance. Three identical specimens were tested for each material with strain gauges and one specimen with extensometer. Strain gauges were fixed in the direction parallel and perpendicular to the loading direction to obtain elastic moduli (E_L and E_T) and poissons ratios (ν_{LT} and ν_{TL}). Table 4.1 summarizes the results of

static tensile tests of glass/epoxy composites. The tensile properties of unidirectional (Kevlar and carbon composites) are presented in Table 4.2.

Elastic modulus determined using extensometer was observed to be lower than that obtained using strain gauges for all composites except for random glass composite in which case it was slightly higher. In the case of carbon composite the difference was less than 1% and for the other three materials, it was in between 10% and 15%. This may be due to the difference in measuring strains by these two methods, i. e., the extensometer was mounted on the thickness face(edge) of the specimen while strain gauges were mounted on the flat face. Moreover, the extensometer gauge length was four times that of the strain gauges used. Since the Iosipescu shear test and its suitability for these materials were the objective for the present study, no detailed studies were carried out to explain the discrepancy in measuring the longitudinal modulus by the above mentioned methods.

O'Brien et.al. [36] studied the effects of gauge length on tensile stiffness measurements using both extensometer and various types of strain gauges. They observed the tensile response to be piece-wise linear till failure for strain gauges, with changes in slopes occurring at discrete damage events under the strain gauges. Whereas, the extensometer response being an integration of discrete damage events occurring within the gauge section and is smooth but non linear till failure. Their studies also reveal the effects of measuring strain on the epoxy or smooth side of specimen and that of scrim cloth side. The strain measurements on the scrim side yielded

E-GLASS COMPOSITES	MODULUS GPa E_L, E_T	AVERAGE PROPERTIES E_L, E_T	ν_{LT}, ν_{TL}
COARSE CLOTH GLASS COMPOSITE		28.365	0.221
EXTENSOMETER	27.11		
STRAIN GUAGE	29.62		
FINE CLOTH GLASS COMPOSITE		32.56	0.215
EXTENSOMETER	30.89		
STRAIN GAUGE	34.24		
RANDOM GLASS GLASS COMPOSITE		17.43	0.376
EXTENSOMETER	17.89		
STRAIN GUAGE	16.965		

TABLE 4.1 TENSILE PROPERTIES OF E-GLASS COMPOSITE

TENSILE PROPERTIES	KEVLAR	CARBON
MODULUS GPa		
EXTENSOMETER		
E_L	58.271	88.76
E_T	1Ø.582	9.595
STRAIN GAUGE		
E_L	66.Ø6	89.36
E_T	1Ø.21	9.68
AVERAGE PROPERTIES		
MODULUS GPa		
E_L	62.17	89.Ø6
E_T	1Ø.394	9.64
POISSONS RATIO		
ν_{LT}	Ø.342	Ø.3442
ν_{TL}	Ø.Ø3196	Ø.Ø299

TABLE 4.2 TENSILE PROPERTIES OF UNIDIRECTIONAL COMPOSITE.

moduli less than that of epoxy side. But the authors have not presented an explanation of these results.

4.2 IN-PLANE SHEAR BEHAVIOUR :

Iosipescu shear tests were conducted on all the five materials considered for determining their shear modulus as well as shear strength. The specimens used were of dimensions 80 x 20 x 3 mm with tabs fixed on to the ends to alleviate crushing at the loading points. Two specimens were tested in each case for determining shear modulus and three specimens for shear strength. In the case of unidirectional composites (Kevlar and carbon), tests were performed for both 0° and 90° specimens. For the three types of E glass/epoxy composites, tests were conducted only for one fibre orientation, since the type of reinforcement used makes the material properties same in L and T directions. Details about the test fixture and specimens have already been discussed in an earlier section.

The Iosipescu tests were performed in compression mode. In each case two identical specimens were tested in load control and one specimen under stroke control to determine ultimate shear strength. For shear modulus, two identical specimens were tested. Shear strain was measured using strain gauges mounted on either side of the specimen at specimen mid-length along the principal stress directions, i. e., $\pm 45^\circ$ to the loading axis. The shear modulus of these composites were obtained from the stress-strain diagram. The shear modulus was calculated from the stress corresponding to 0.2 % shear strain, i. e., the secant modulus at 0.2 % shear strain. A typical stress-strain diagram showing the measurement of shear

modulus by the above mentioned method is presented in Fig. 4.1.

The load-displacement diagrams were obtained from the X-Y recorder of the testing machine during shear strength tests. The initial portion of load-displacement curve was linear for all materials. However, beyond a certain load or stress, the slope of the curve continuously drops. This corresponds to the initiation and growth of damage within the test section accompanied by large deformation of the specimen. It was assumed that shear failure of the material occurs at the load corresponding to flattened portion of the load (or stress)-displacement plot. A typical load-displacement curve showing the damage initiation point is presented in Fig 4.2. In each case the load or stress corresponding to this point was used for calculating ultimate shear strength.

The three glass/epoxy composites fracture behaviour and shear properties are compared in the following section. The shear response of unidirectional composites (carbon and Kevlar composites) are discussed in a latter section.

4.2.1 SHEAR BEHAVIOUR OF E-GLASS/EPOXY COMPOSITES :

The results of Iosipescu shear tests on glass/epoxy composites are summarized in Table 4.3. Fig. 4.3 gives the stress-strain diagram of these materials. Typical load-displacement curves obtained from the X-Y recorder are presented in Fig. 4.4

FRACTURE AND FAILURE PATTERN :

There were no clearly defined cracks on the specimen during strength tests of glass/epoxy composites. Beyond a certain load, the damage was initiated at the notch root which was visible

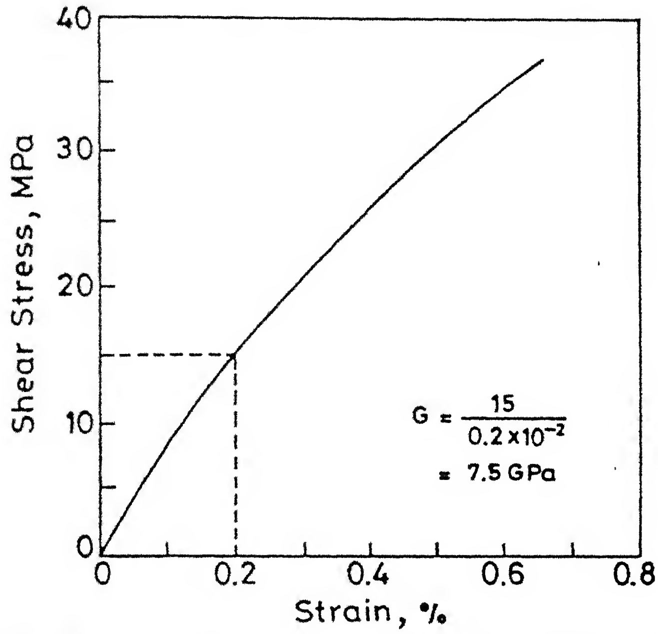


Fig. 4.1 A typical shear stress-strain diagram showing the 0.2 % secant modulus method.

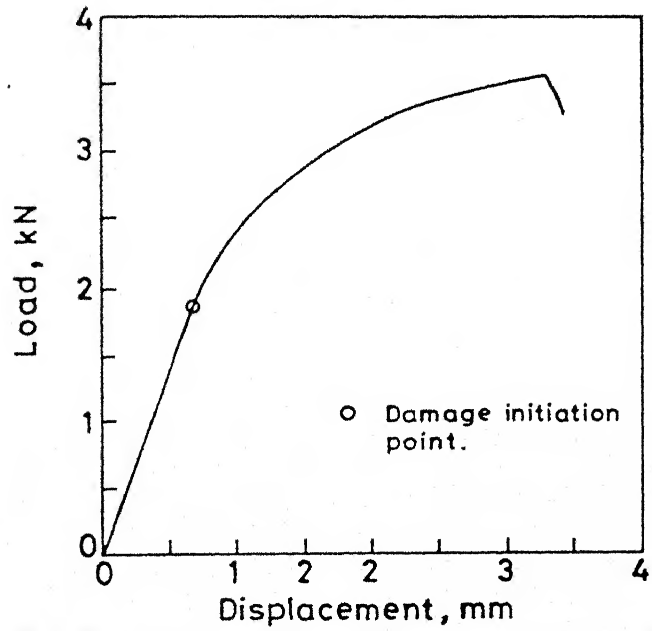


Fig. 4.2 A typical load-displacement diagram showing the damage initiation point.

MATERIALS	SPECIMEN CODE	IN PLANE SHEAR PROPERIES			
		INITIAL SHEAR MODULUS (GPa)	SHEAR STRENGTH (MPa)	AVERAGE SHEAR MODULUS (GPa)	AVERAGE SHEAR STRENGTH (MPa)
COARSE GLASS EPOXY	1 2 3	6.5 5.986 -	47.58 54.43 44.97	6.243	48.993
FINE GLASS EPOXY	1 2 3	6.4 6.421 -	80.56 83.604 79.50	6.4105	81.221
RANDOM GLASS EPOXY	1 2 3	8.41 8.95 -	97.391 109.640 96.960	8.68	101.33

TABLE 4.3 SHEAR PROPERTIES OF E-GLASS COMPOSITES

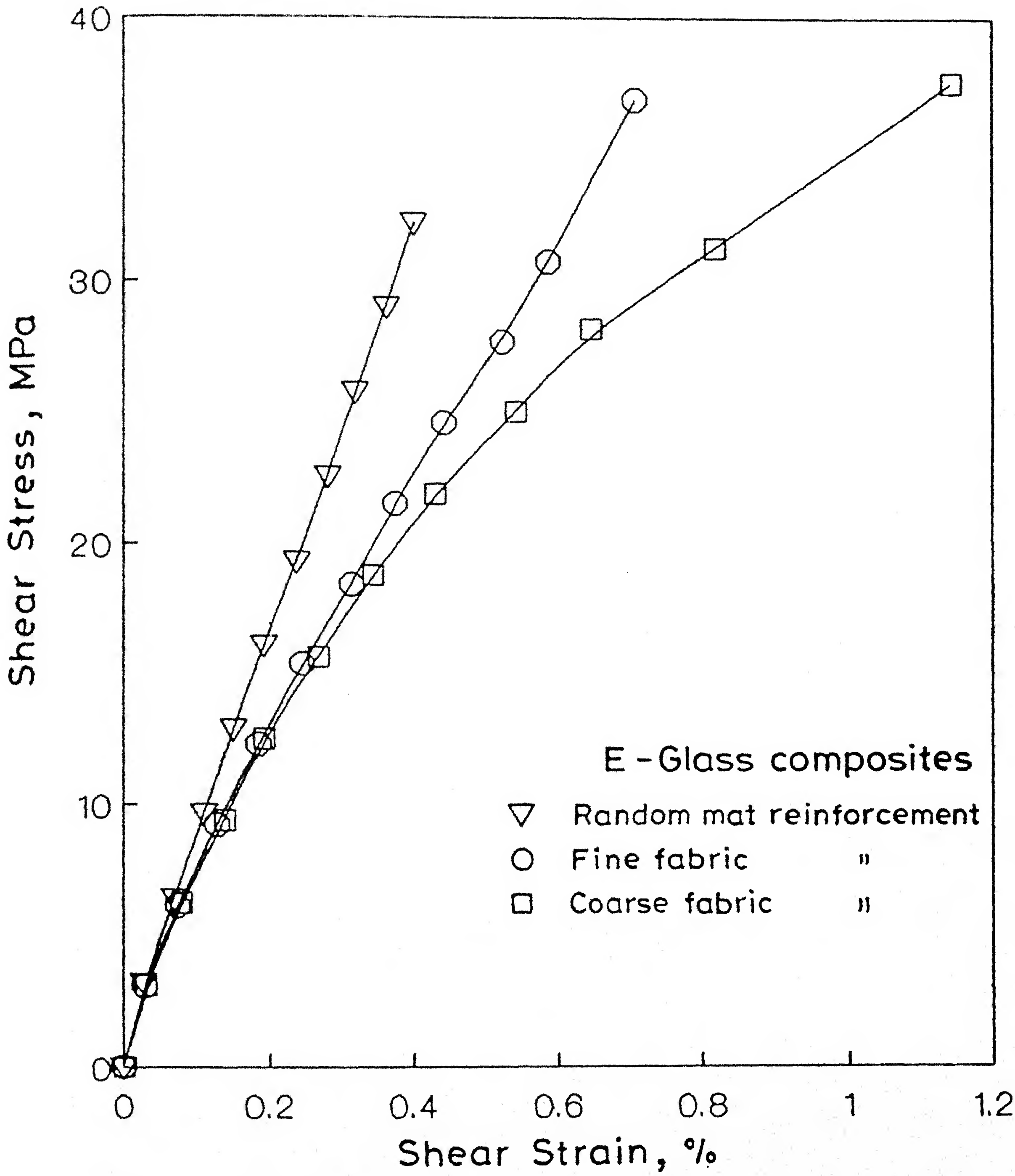


Fig. 4.3 Shear stress-strain diagram for glass composites.

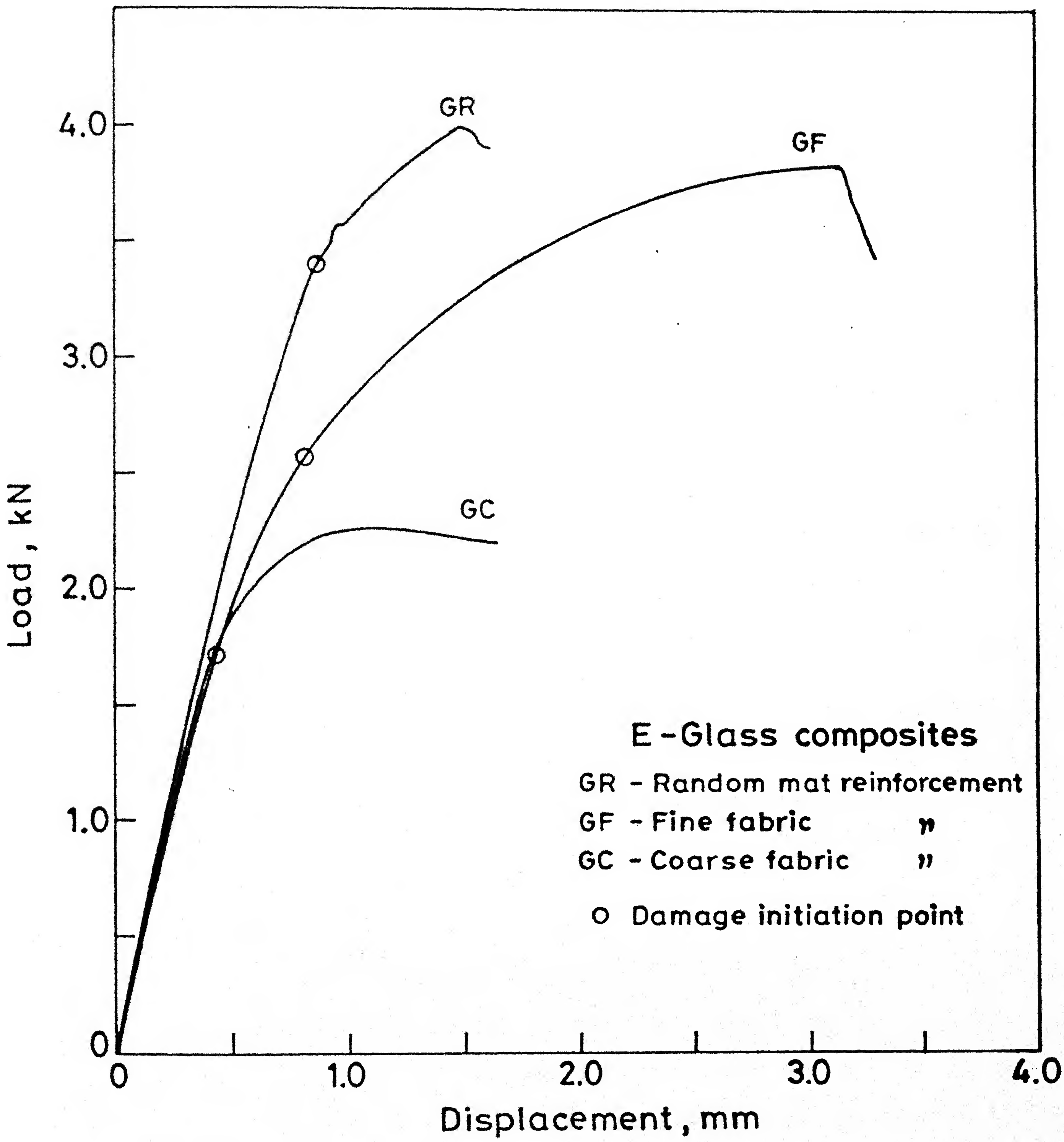


Fig. 4.4 Load-displacement diagram for glass-composites.

as whitening of these materials at the test section. Damage initiation was accompanied by large deformation of specimen and corresponds to the the flattened portion of load (stress)-displacement diagram. The specimens continued to take load gradually till the gross final failure. Prior to failure, cracks were seen, which in most of the cases ran along the damage growth line. Fig. 4.5 gives the failure pattern of glass/epoxy composites schematically.

In the case of fine glass cloth composites, damage was initiated close to the notch roots and extended in a line joining them (Fig. 4.5a). The damage zone was quite narrow compared to other materials. There was small local orientation of fibres at test section. The fracture of the specimen was clean without any fibre pullout and along a single vertical plane at notch roots, i. e., fibres at test section failed in shear.

For coarse glass cloth composite specimens, damage zones from the notch roots were extended in two stages. Initially, damage occurred at the notch roots on either face of the specimen and extended in the direction of inner loading points (Fig. 4.5b). This was followed by considerable deformation of specimen and spread of damage zone at test section. In the mean time some local orientation of fibres took place and the specimen continued to take further load. These orientations were more than those occurred in fine glass cloth composite specimens. A second damage was initiated at this time near the notch roots (see Fig. 4.5b). The final failure was accompanied by fibre pullout. The fracture surface was not in a single plane. In this case most of the fibres failed in shear and

some of them in tension.

Figure 4.5c gives the failure pattern of random glass composite specimen. The final fracture of the specimen took place in one of the two ways as shown in Fig. 4.5c. For both the cases, damage first occurred at the bottom notch root and extended towards the left top edge of the specimen. In these specimens damage zone is much more spread and edge crushing was noticed at the inner loading points. The second damage zone started either from the left top edge or from the top notch root. Final fracture occurred along these first and second damages zones. The photograph of E glass/epoxy fractured specimens are given in Fig. 4.6.

The studies of Voloshin and Arcan [37] on failure of fibre reinforced composite under bi-directional state of stress resulted in understanding the failure surface for different modes of failure,i. e., corresponds to pure shear, shear + tension and shear + compression. The main characteristics of pure shear mode are debonding of fibre from the matrix and preserving failed fibres in the direction of shear. Fibre surfaces were seen without matrix on it showing that failure occurred at interface between fibre and matrix. The shear + tension case is characterized by irregularity of the failure section and brush like mode is clearly observed. As a result of fibre pull-out, failure surface is far away from to be a plane. The shear + compression case may be characterized by multitude of small pieces of broken matrix. The failure surface is essentially flat and parallel to the significant section, no pull-out of fibres were observed. Failure generally occurred in the interface between fibre and matrix , like in the pure shear case.

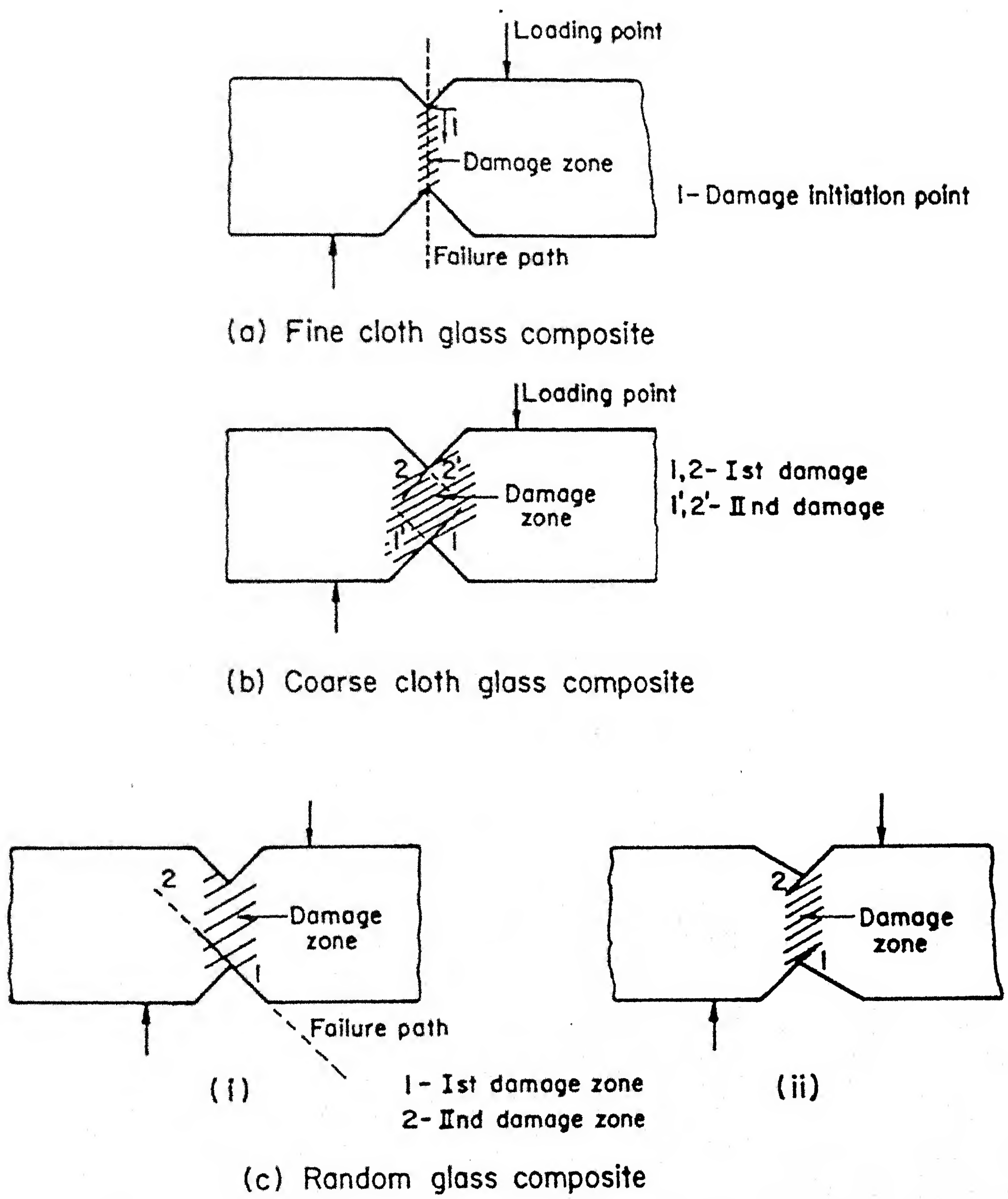


Fig.4.5 Failure patterns of E-glass composites

a)

b)

c)

d)

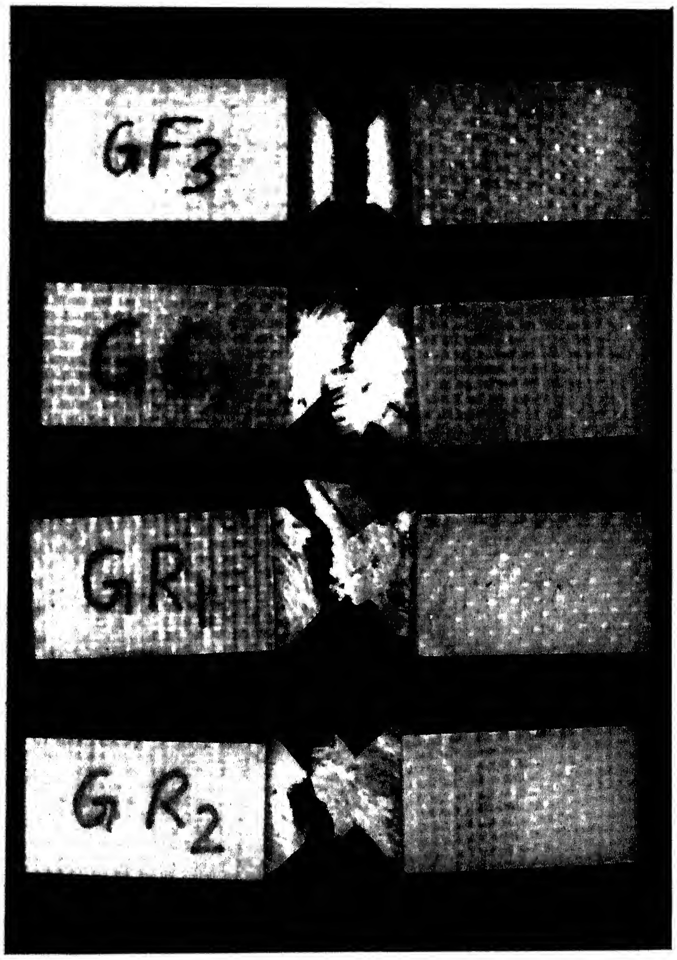


FIG. 4.6 FRACTURED IOSIPESCU SPECIMENS OF E-GLASS COMMPOSITES.
a) FINE GLASS COMPOSITE
b) COARSE GLASS COMPOSITE
c) & d) RANDOM GLASS COMPOSITE

mat

SHEAR MODULUS AND SHEAR STRENGTH :

Looking at the data of Table 4.3, we see that, in-plane shear modulus of coarse cloth glass composite and fine cloth glass composite are not varying significantly. The shear modulus is maximum for random glass composite. The initial modulus is changing from random glass composite to coarse glass composite. The shear behaviour of these materials are more clear from the shear stress-strain and load-displacement diagrams of these materials. (Fig. 4.3 and 4.4). From the shear stress-strain plot, we can see that, at low stress levels they are very close with slope falling from random glass composite to coarse glass composite. Also the graph is linear for random glass composite showing good shear qualities, whereas, fine glass composite response is almost linear and coarse glass composite shows non-linearity after a stress level of 5 MPa. The ultimate shear strength of these materials shows large variation from random glass composite to coarse glass composite.

The higher stiffness and strength of random glass composite may be expected due to the presence of fibres other than 0° and 90°. The shear modulus of composites are minimum when fibres are parallel and perpendicular at 0° and 90° to the loading axis and is a maximum for fibres oriented at 45°. The values of shear strengths obtained for random glass composites are comparable with the results of Adams and Walrath [5] for random glass (SMC) composites. In the case of randomly oriented fibrous composites, no matter what orientation of in-plane shear loading is applied, some of the randomly oriented fibres are loaded in transverse shear. Thus the fibres tend to both strengthen and stiffen the material during

in-plane shear loading. Also some fibres are loaded in tension irrespective of the direction of applied shear. Moreover, a crack or damage always encounters resistance to propagation from some fibres.

The difference in shear property values of fine glass composites and coarse glass composites are due to the better material property of former compared to the latter, evident from the static tensile data. i. e., the low denier fibres in fine weave will have better shear property than plied yarn in coarse weave. The stress distribution in the fine glass composite will be better than that of coarse glass composite. Moreover, the size and size distribution determines the interfacial area between the matrix and fibre . For shear loading the interface plays an important role in load carrying capacity of the material. From the Table 4.3 we can see That the difference is more significant in their ultimate shear strength values.

4.3 SHEAR BEHAVIOUR OF UNIDIRECTIONAL COMPOSITES :

In the case of unidirectional composites both 0° and 90° specimens were tested. For both carbon Kevlar composites 0° specimens deformed considerably more than the 90° specimens. In the case of 0° specimen, the shear behaviour was fibre dominant, whereas, for 90° specimen it was matrix dominant. Tests were also performed on carbon composites with fibre orientation as a variable with respect to loading axis.

The effect of fibre orientation in shear tests of composites are yet to be answered. Ideally there should not be any effect for 0° or 90° fibre orientation of fibres. However, most of the shear tests employing specimens of 0° and 90° fibre

orientations showed variation in shear modulus and strength values due to the nonuniformity of shear stress at test section. Shear tests with different fibre orientations calls for more difficulty due to coupling effects and produce inaccurate results.

Most of the shear tests proved to be suitable for composite materials though simple to conduct are not suitable for performing experiments with varying fibre orientations. Some of these tests fixes the fibre orientation of the test material (10° off-axis tensile test and $\pm45^\circ$ tensile test). For others, the loading scheme employed (rail shear test, picture frame test etc.) will not permit different fibre orientation due to the loading point constraints to the coupling effects.

Iosipescu shear test is comparatively new for shear characterization of composites. The test configuration permits the use of specimens with different fibre orientations with respect to loading axis. The present study asses the suitability of Iosipescu shear test for determining shear response of unidirectional composites with varying fibre directions.

4.3.1 SHEAR BEHAVIOUR OF CARBON COMPOSITES :

Tests were performed on carbon composites with fibre orientation as a variable with respect to loading axis. Specimens with fibre directions varying from 0° to 90° in steps of 15° were tested. The results of these tests are presented in Table 4.4. Fig. 4.7 gives the stress-strain diagrams of carbon composite with 0° to 45° fibre orientations. Corresponding load-displacement curves are presented in Fig. 4.8. Stress-strain diagram and load-displacement

CARBON COMPOSITE FIBRE ORIENTATION, DEG.	NO:	IN-PLANE SHEAR PROPERTIES			
		SHEAR MODULUS GPa	SHEAR STRENGTH MPa	AVERAGE SHEAR MODULUS GPa	AVERAGE SHEAR STRENGTH MPa
0°	1	7.342	68.134	7.46	67.1
	2	7.59	66.78		
	3	-	66.39		
15°	1	7.395	75.57	7.41	67.66
	2	7.421	66.81		
	3	-	60.66		
30°	1	8.528	42.115	8.39	40.48
	2	8.252	41.12		
	3	-	38.19		
45°	1	9.53	51.15	10.13	35.965
	2	10.74	39.19		
	3	-	32.74		
60°	1	7.98	33.84	8.38	32.58
	2	8.78	35.89		
	3	-	28.00		
75°	1	6.84	33.63	7.18	38.03
	2	7.36	44.26		
	3	-	36.21		
90°	1	7.12	46.30	6.94	43.69
	2	6.75	46.71		
	3	-	38.073		

TABLE 4.4 SHEAR PROPERTIES OF CARBON COMPOSITES FOR 0° TO 90° FIBRE ORIENTATIONS.

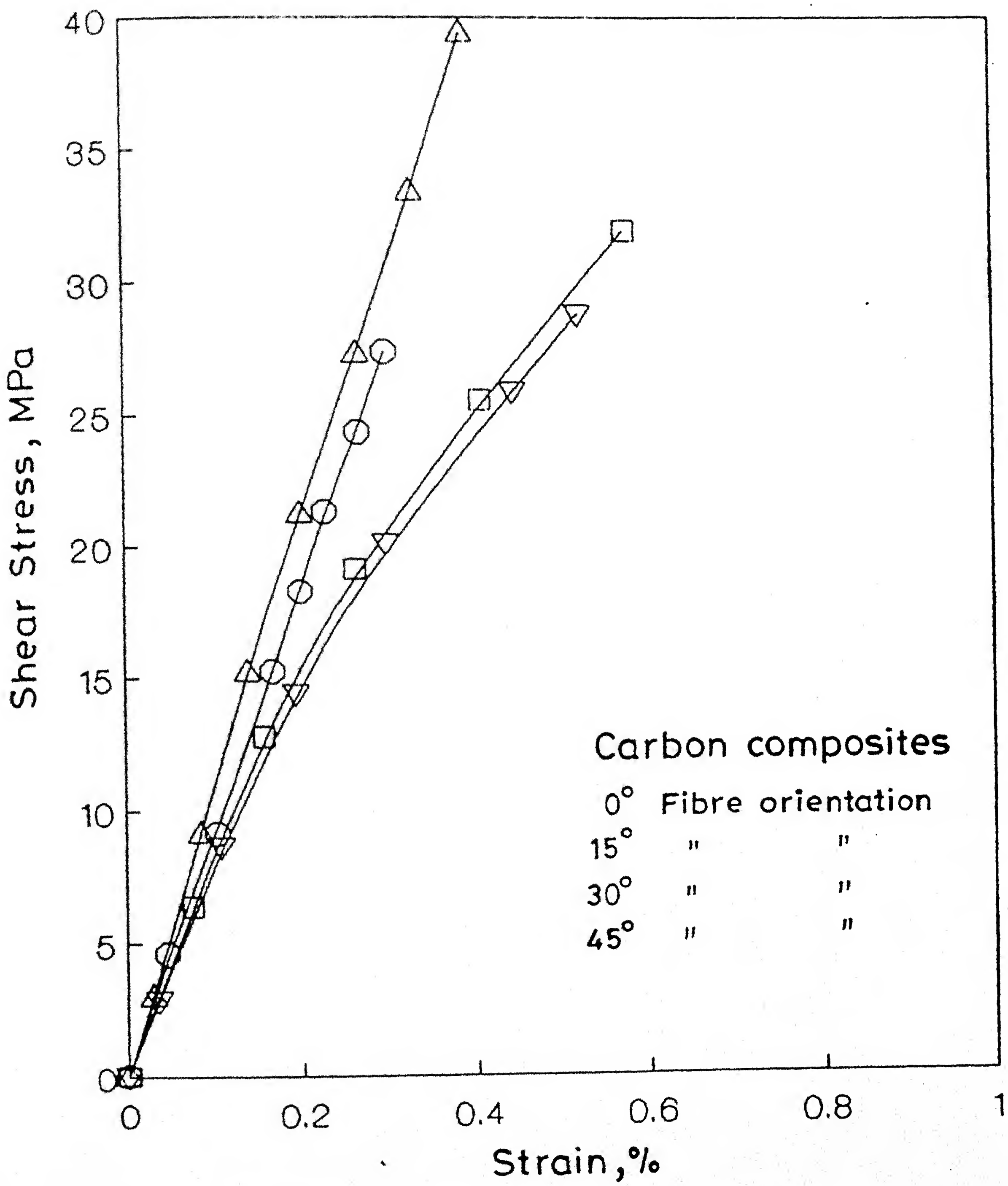


Fig. 4.7 Shear stress-strain diagram for carbon composites.

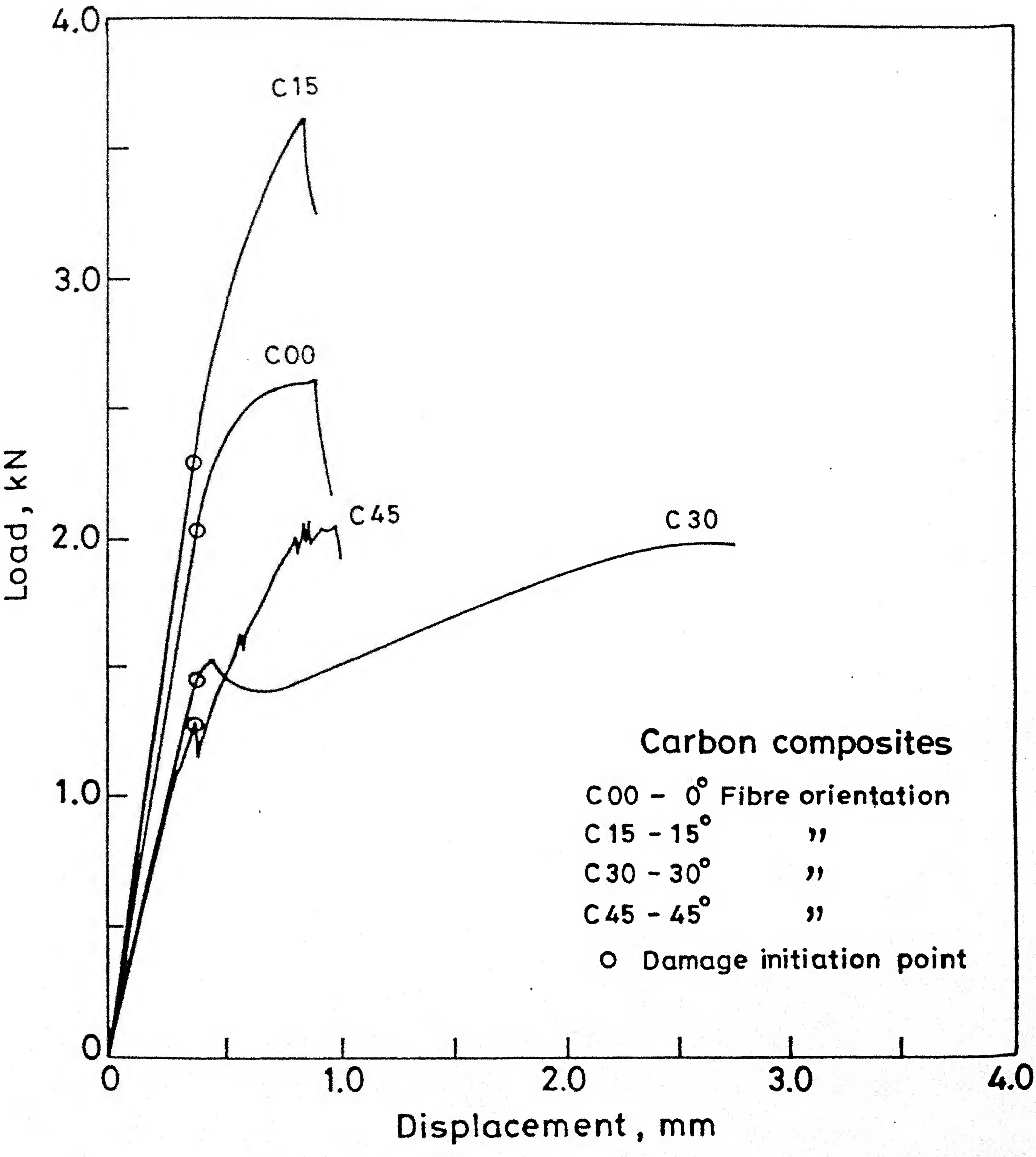


Fig. 4.8 Load-displacement diagram for carbon composites.(for fibre orientations 0°, 15°, 30° and 45°)

curves for carbon composite specimens with fibre orientations ranging from 45° to 90° are given in Fig. 4.9 and Fig. 4.10 respectively.

FRACTURE AND FAILURE PATTERN :

During the shear strength tests on carbon composite with different fibre orientations with respect to loading axis, failure took place initially at notch root in all cases and extended in a direction parallel to fibres. The fracture behaviour of these specimens can be grouped into three. In the case of 15° and 30° fibre orientations, the fracture behaviour were similar to that of 0° specimen, whereas, for 60° and 75° fibre directions, failure modes were comparable to 90° specimens. For 45° specimen the failure occurred was in-between these two cases, i. e., that of 0° and 90° fibre orientations.

The fracture of carbon 0° specimen was typical. After the linear portion of load-displacement curve (Fig.4.7), there was a sudden change in the slope corresponds to axial splits located immediately after the notch tips. The axial splitting of 0° specimens of unidirectional composites were observed by Adams and Walrath [30] and Sullivan et. al. [33]. Because of material orthotropy in unidirectional composites, a stress concentration exists at the notch roots. It is believed that shear coupling deformations along the notch flank imposes a redistribution of stresses at test section, resulting in stress concentration. Numerical investigations carried out by Adams and Walrath [30] show the presence of transverse normal tensile stresses, to the left of the top notch root and to the right of bottom notch root for both

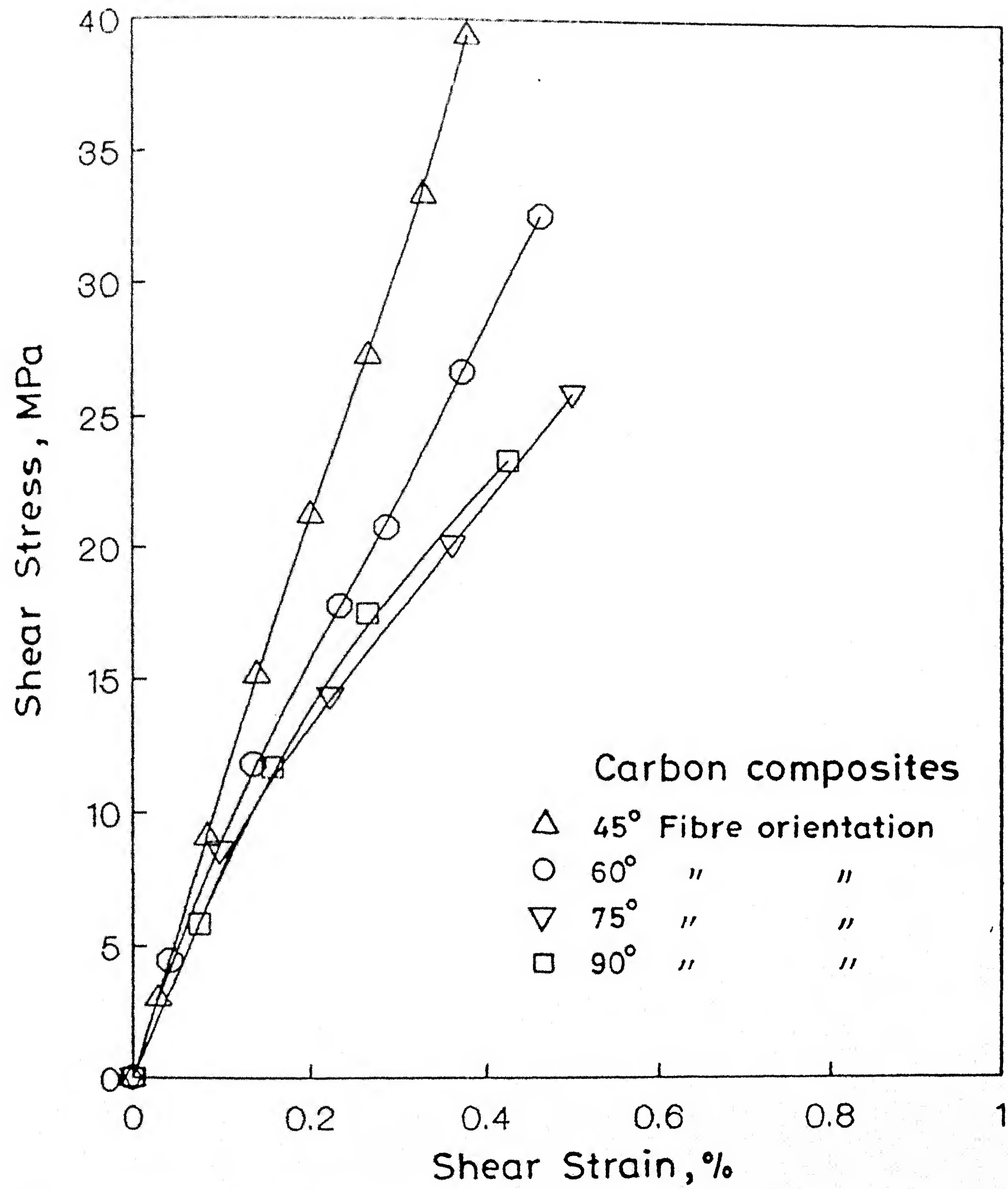


Fig. 4.9 Shear stress-strain diagram for carbon composites.

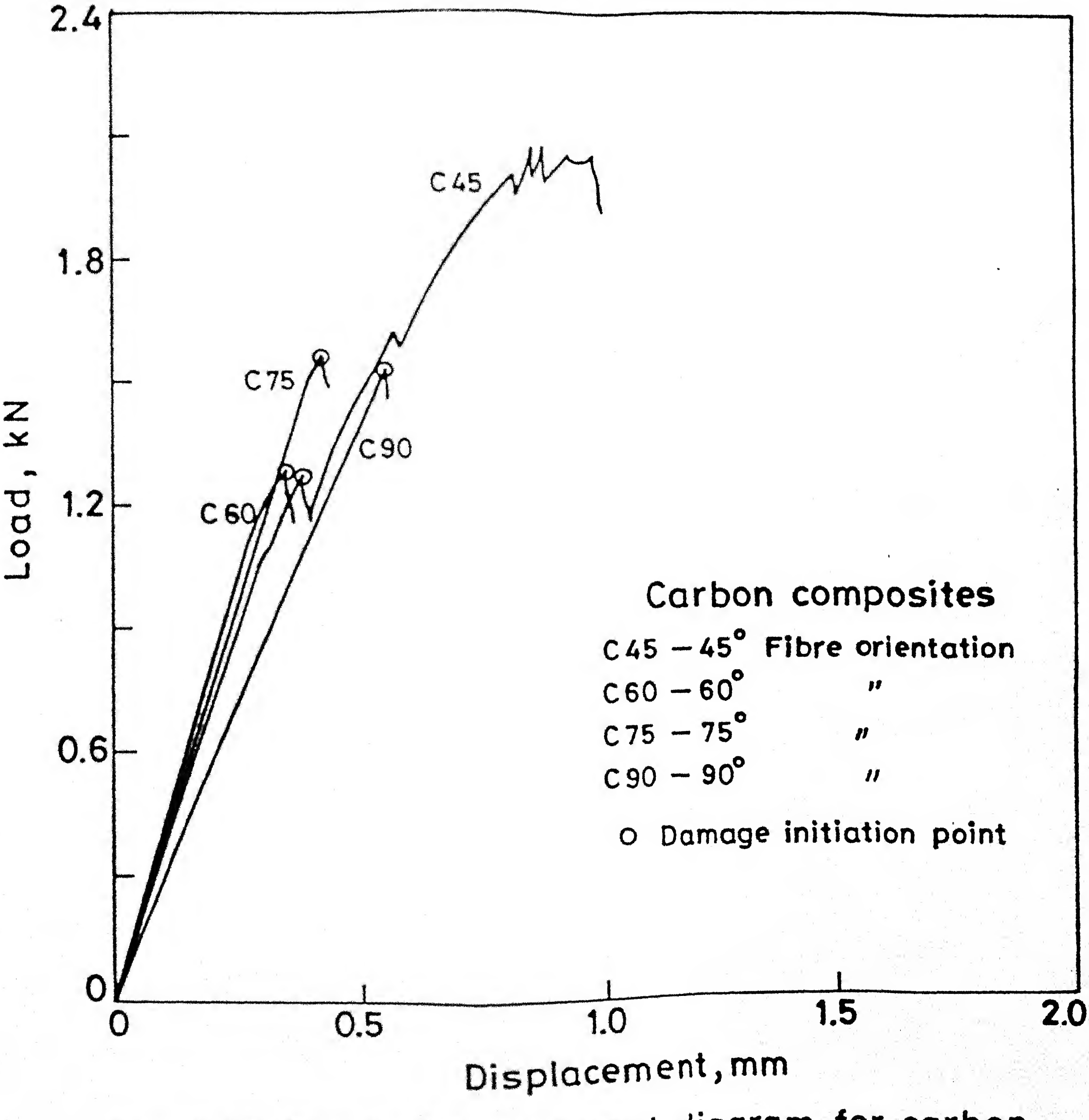


Fig. 4.10 Load-displacement diagram for carbon composites (for fibre orientations 45°, 60° 75° and 90°)

the 90° and 110° specimen configurations. This stress is probably inherent in the test method and can not be totally eliminated. The presence of transverse normal stress along with shear stress at this location causes the axial split, propagating parallel to fibres, away from the inner loading point. A schematic diagram of the 0° specimen with axial split is shown in Fig. 4.11a.

Further loading of specimen was possible after the splits occurred, leading to a large deformation of specimen. Also there was visible rotation of fibres adjacent to the notches (Fig. 4.11a). At this point, the fibres were taking a portion of load in a tensile mode. The axial splits extend as the loading continued and final gross failure occurred. Fine cracks were also formed along the fibre direction and between the notches prior to failure.

The 15° and 30° fibre orientations of carbon composites, the failure were similar to that of 0° specimen. The damage (split) initiated at the top and bottom notches and extended along the fibre direction, away from the inner loading points. After the final failure, the openings of the split for both the cases were more than 0° specimen. Also 15° specimen took more load after the split had initiated, fibres at test section undergone small rotation and sudden failure occurred after reaching maximum load compared to the other two cases. The 30° specimen deformed much more than 0° specimen after the split initiation, experienced large rotation of the specimen from initial position till fracture and correspondingly the opening of the split was maximum compared to the other two cases. For 15° and 30° fibre directions, the fibres at test section were perpendicular to the loading directions at final fracture. In

all the three cases even after complete failure during strength tests, the specimen halves were not separated and fine cracks were seen at test section. The fineness and number of cracks were decreasing from 0° to 30° fibre orientation.

In the case of 90° specimens of carbon composites, after the linear portion of the load (stress)-displacement plot, specimens failed suddenly due to the crack running parallel to the fibres and between the notches at test section (Fig. 4.11b). They did not take much load after the crack. No damage zone was visible on the specimen during testing. Some of the 90° specimens of carbon composites failure was accompanied by splitting of specimen along the fibres in the region of load application. Adams and Walrath [30] had reported unfavorable load distribution at the inner loading surfaces, resulting in very high compressive forces directly at the edge of the loading surface. Obviously for these specimens failure occurred outside the test section (Fig. 4.11c). This was also reported by Pindera et. al. [35] and found that the average failure shear stress for specimen failing at test section or outside were not anomalously different.

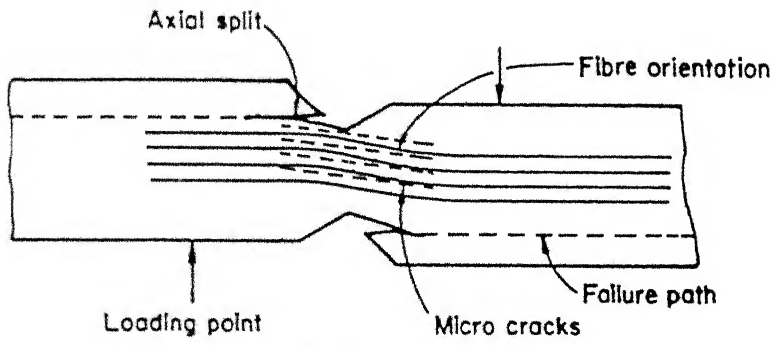
The 60° and 75° specimens of carbon composite failures were comparable with that of 90° specimen. In both the cases the specimen did not take much load after damage (crack) initiation and failed suddenly. Also the split emanated form the vicinity of top notch root extended parallel to the fibre direction. The final failure resulted in two specimen halves. In the case of 60° fibre orientation, one specimen failed by the cracks emanating from top and bottom notch roots extended towards the bottom and top inner loading points. This resulted in three specimen parts with a small

central portion other than the two specimen halves; which came out of the specimen sides at test section. The fracture surface was smooth and no fine cracks were seen between the notches at test location.

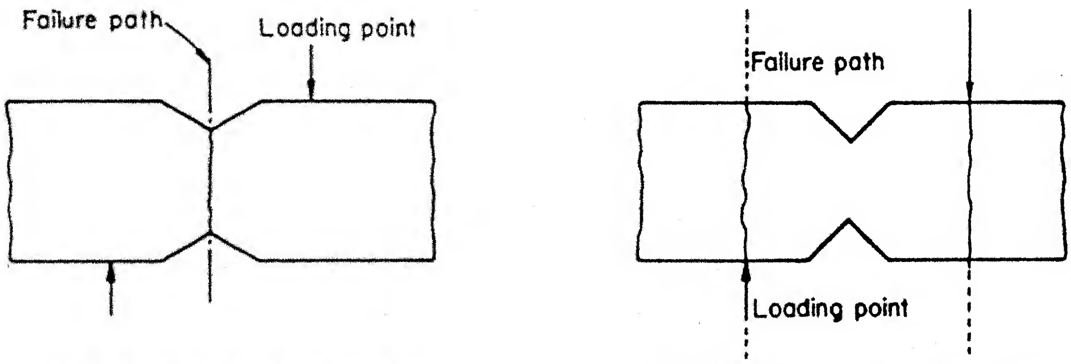
For 45° specimens of carbon composites during strength test the fracture initiated from both the notch root. On further loading they extended along fibre direction towards the loading edges. The fibres between the notches got oriented from the initial position as the split extends during failure. The final fracture resulted in three specimen portions, consisting of a small central portion other than the two specimen halves; which came out of the specimen sides at test location. These specimens carried much load after the initial split compared to 60° specimens. But their failure were fast compared to 30° specimen and they could carry only less load after the damage initiation. There were no fine cracks visible at the test location between notch roots. Fig. 4.11d gives the failure pattern of 45° specimen schematically. The Photograph of carbon composite specimens fractured in shear tests are given in Fig.4.12a (for 0° to 30° specimens) and in Fig. 4.12b (for 45° to 90° specimens).

SHEAR MODULUS AND SHEAR STRENGTH :

Table 4.5 summarizes the average shear modulus of Iosipescu shear test and theoretically determined shear modulus for all fibre orientations using the four independent elastic constants. The graph of these results are plotted against fibre angle in Fig. 4.13. Fig. 4.14 shows the variation of ultimate shear strength for



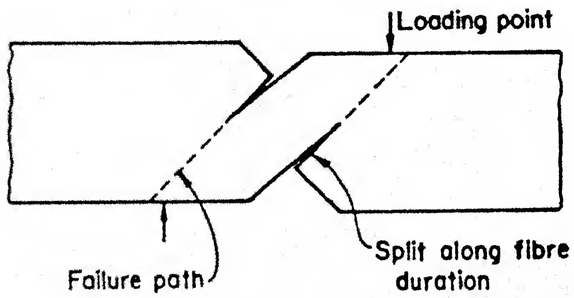
(a) 0° Carbon specimen



(i) Failed inside test section

(ii) Failed outside test section

(b) 90° Carbon specimen



(c) 45° Carbon specimen

Fig.4.11 Failure pattern of carbon composites

a)

b)

c)

d)

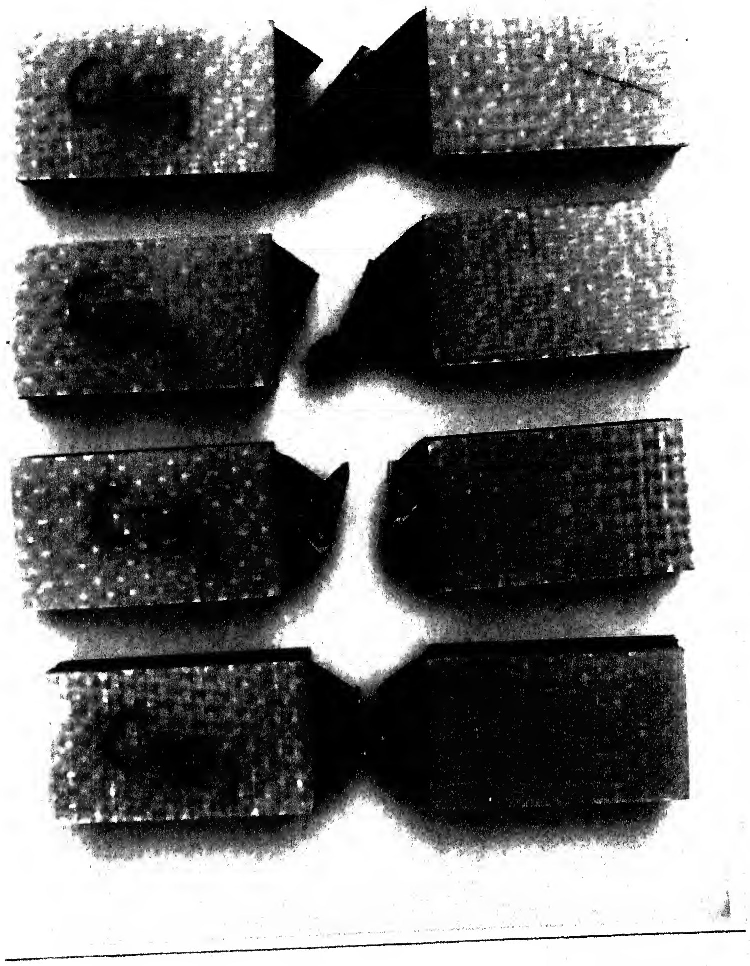


FIG. 4.12b. FRACTURED IOSIPESCU SPECIMENS OF CARBON COMMPOSITES FOR FIBRE ORIENTATIONS 45° TO 9Ø°.

a) 45° SPECIMEN
b) 6Ø° SPECIMEN
c) 75° SPECIMEN
d) 9Ø° SPECIMEN

a)

b)

c)

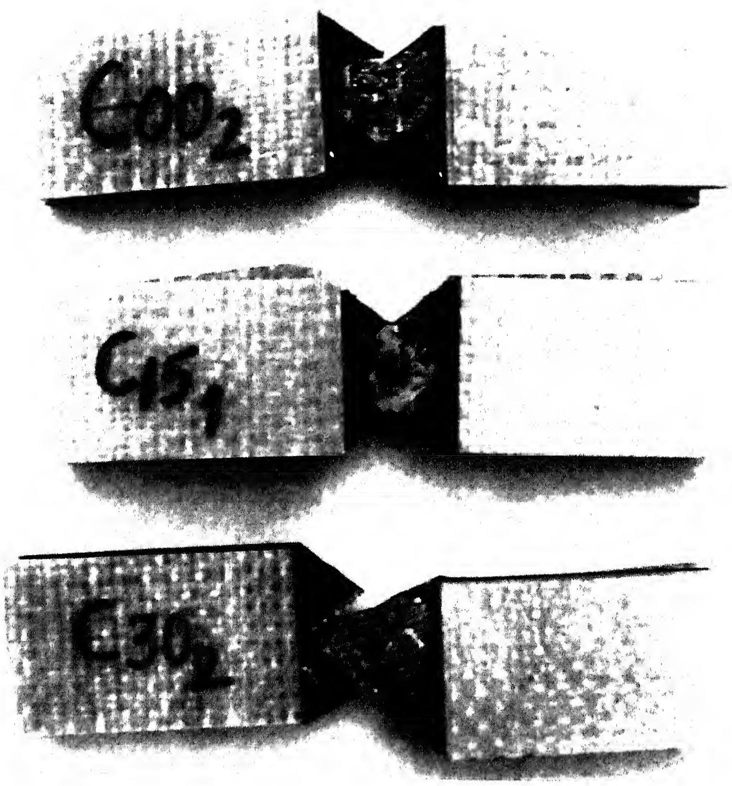


FIG. 4.12a FRACTURED IOSIPESCU SPECIMENS OF CARBON COMMPOSITES FOR FIBRE ORIENTATIONS Ø° TO 3Ø°.
a) Ø° SPECIMEN
b) 15° SPECIMEN
c) 3Ø° SPECIMEN

CORBON COMPOSITE FIBER ORIENTATION	MEASURED SHEAR MODULUS Gxy (GPa)	$\frac{Gxy}{GLT}$	THEORETICAL SHEAR MODULUS Gxy (GPa)	$\frac{Gxy}{GLT}$
0°	7.46	1	7.46	1
15°	7.41	0.994	7.62	1.021
30°	8.39	1.125	7.98	1.07
45°	10.13	1.357	8.16	1.094
60°	8.36	1.123	7.98	1.07
75°	7.13	0.96	7.62	1.021
90°	6.94	0.93	7.46	1.000

TABLE 4.5 SHEAR MODULUS (EXPERIMENTAL AND THEORETICAL) OF CARBON COMPOSITES WITH 0° TO 90° FIBRE ORIENTATION.

different fibre orientation.

Theoretically there should not be any effect for 0° or 90° orientation of fibres for pure shear loading. Also the theoretical shear modulus is same for 15° and 75°, 30° and 60° fibre orientations. It is a maximum for 45° specimen. Theoretical modulus for these fibre orientations was calculated using the relation

$$1/G_{xy} \text{ or } 1/G_\theta =$$

$$[(1/E_L + 2 \times {}_{LT}/E_L + 1/E_T) -$$

$$(1/E_L + 2 \times {}_{LT}/E_L + 1/E_T - 1/G_{LT}) \cos^2 2\theta]$$

Where,

G_{xy} or G_θ - is the shear modulus for fibre orientation θ with respect to the loading axis.

E_L - longitudinal elastic modulus

E_T - transverse elastic modulus

ν_{LT} - major poissons ratio

G_{LT} - shear modulus for 0° fibre orientation from Iosipescu test

Due to the loading geometry, the principal stress directions are oriented at $\pm 45^\circ$ with respect to the loading axis. For 0°, 45° and 90° fibre orientations, ideally, principal strain directions are also oriented along that of principal stress directions. For fibre orientations other than 0° and 90°, normal stresses and strains are induced at the test section. They deviate the above mentioned principal stresses and strains from $\pm 45^\circ$ to the loading axis and affects the shear stress distribution at test section.

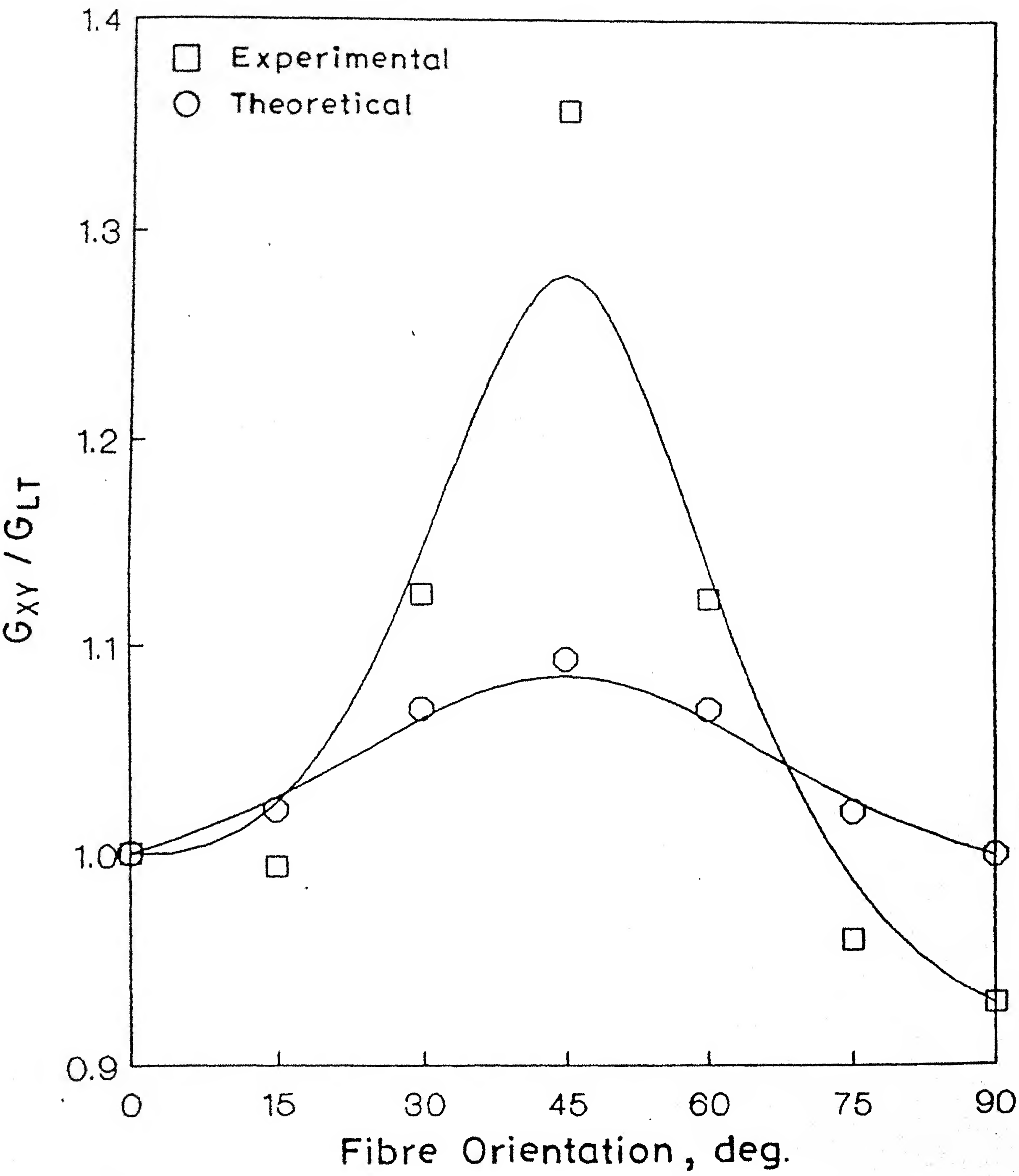


Fig. 4.13 The variation of normalized shear modulus for different fibre orientations.

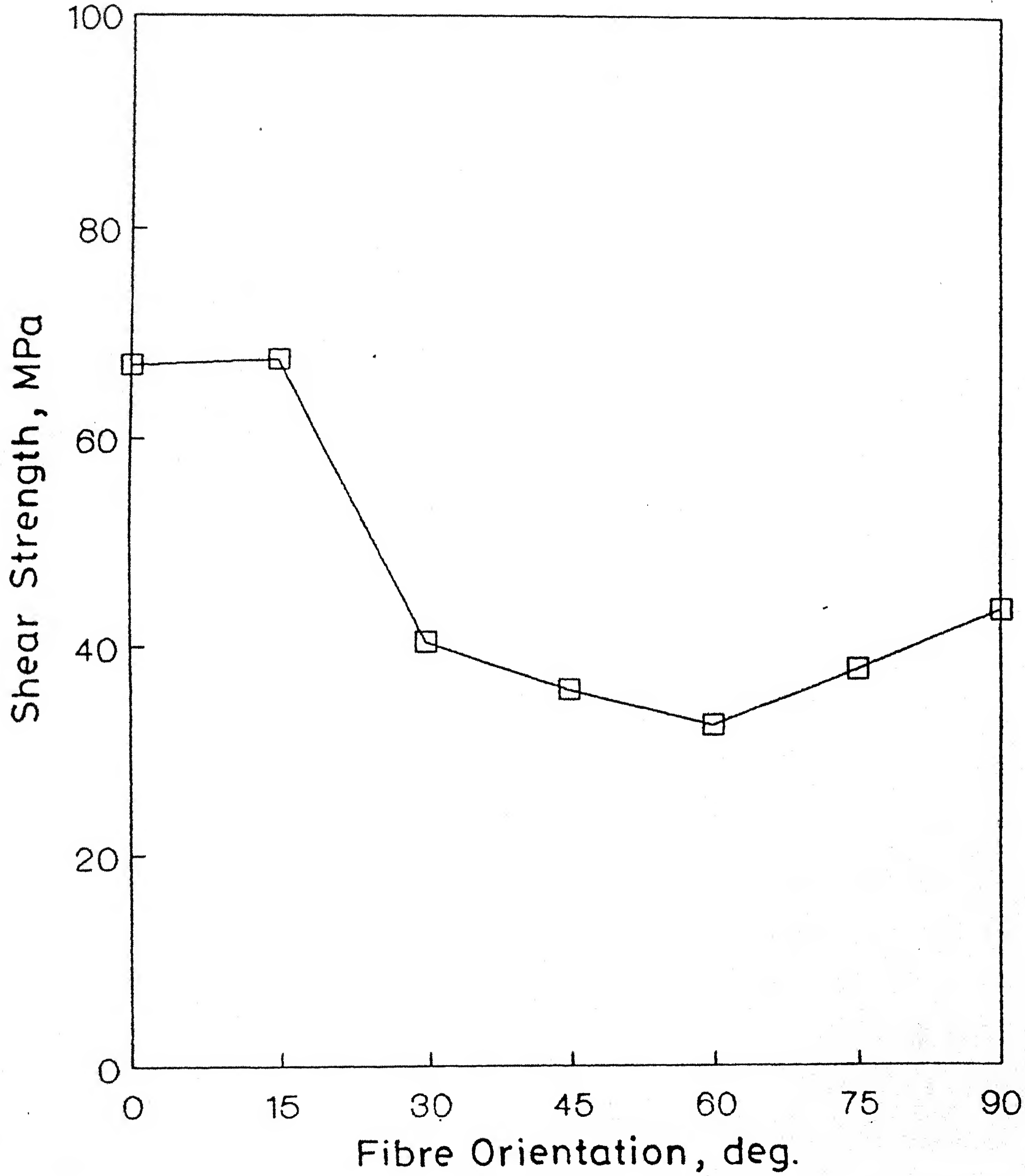


Fig. 4.14 The variation of shear strength with respect to fibre orientation.

From the data of Table 4.4 we see that the shear modulus of 0° specimens of both Kevlar and carbon composites are higher than that of 90° specimens. Numerical studies of Pindera et. al. [35] showed that the stress reaches a maximum at the test section for the 0° fibre orientation while for the 90° fibre orientation the shear stress at this location is a minimum. i. e., non-uniformity of shear stress along center-line between the notch roots. Consequently, for the 0° specimen, the experimentally measured shear modulus will be more than that of 90° specimen.

From table 4.5 we see that the trend in the theoretically calculated and experimentally measured shear modulus are same (Fig. 4.13). The shear modulus of 15° specimen was slightly less than 0° specimen, whereas, 75° specimen was between 0° and 90° fibre orientation. For 30° and 60° specimens, the experimentally measured shear modulus were almost same. Maximum difference by the above two methods was for 45° fibre direction.

The difference in the experimentally measured and theoretically predicted shear modulus is expected due to the nonuniformity of shear stress at test section. Also the cross coefficients and the loading point induced stresses vary from 0° to 90° fibre orientation. They add to the nonuniformity of shear stresses between notches and affects the shear modulus measurement. Since no numerical investigation is performed in the present study, it is not possible to give a quantitative judgment about the effect of fibre orientation on the measurement of shear modulus. The experimentally determined (apparent) shear modulus deviate from the actual value due to small miss-orientation of fibres in

laminate layers and errors in mounting the strain gauges at test location along the principal stress directions. Eventhough their effect on modulus measurement are small, they can not be neglected when the difference by the above two methods is less than 5 %.

Pindera et. al. [35] performed numerical investigation on Iosipescu and 10° off axis tensile test for shear characterization of unidirectional composites. They proposed correction factors which take into account the nonuniformity of shear stress distribution at test section. The discrepancy in the 0° and 90° specimens apparent shear modulus reduced significantly, when the test is properly interpreted and corrected, considering the actual stress distribution in the test section.

For all fibre orientations during shear strength test, failure (split) was initiated at the vicinity of notch tips and extended parallel to the fibre direction. After the split, on further loading, fibres may take start taking load in the tensile mode due to large rotation of the specimen. If the load carried by the fibres are interpreted as being carried by shear in the matrix, anomalously higher shear values are obtained. Therefore, in all the cases, the ultimate shear stress in Table 4.4 corresponds to the average shear stress recorded at the instant of axial splitting at the notch tips.

Looking at the data of Table 4.4 we see that the ultimate shear strength of 0° and 15° fibre orientations are almost same. There is considerable drop in the load carrying capacity in the case of 30° specimen. The ultimate shear stress value of 90° specimen is close to that of 30° specimen. The 45°, 60°, and 75° specimens carried less load compared to other specimens. Fig. 4.14 gives the

variation of apparent shear strength for different fibre angles.

Pindera et. al. [35] performed analytical studies to determine the shear stress distribution of 0° and 90° Iosipescu specimens of aramid/epoxy and graphite/polymide unidirectional composite. The stress distribution and failure mechanism of 0° and 90° fibre directions are also obtained from the report of Walrath and Adams [30]. According to these authors, for 0° specimens the normal stress concentration σ_{xx} at the notch tips, acts parallel to fibres and probably does not contribute to the initiation of cracks along the fibre direction. Also the normal stresses components perpendicular to fibre direction σ_{yy}, is small and compressive along the center-line between notches and vanishes at notch tips. However, since shear stress concentration exists at notch tips and the axial split does contribute a failure of the matrix due to shear loading. Therefore, the average shear stress at the instant of axial splitting corresponds to an upper lower bound on the shear strength. The further load carrying capacity of the specimen can be considered as a structural property than material response as it is presumably depends on fibre orientation. The experimental studies of Swanson et. al. [33] indicated that for 0° Iosipescu specimens the shear strength value obtained were very close to that obtained from torsion tests of thin, unidirectional tubes.

In the case of 90° specimen premature failure was most likely caused by the presence of normal tensile stress concentration σ_{xx} at the notch tip. These acts perpendicular to the fibres and tends to split the specimen along the center-line between notch roots. The presence of even relatively small tensile stress

transverse to the fibre direction can significantly reduce the ultimate load of the specimen. Because of the orientation of applied load with respect to fibre direction, an initiated crack can run unopposed, resulting in complete separation of the 90° specimen.

Thus the load carrying capacity of the specimen corresponds to the resistance to splitting of fibres at the notch root which corresponds to the shear and normal stress concentrations at notch. These stress concentrations depends on the fibre directions. The shear failure stress of 0° and 15° fibre orientations mostly depended on the shear stress (τ_{xy}) concentration, whereas, for 30° and 45° specimens both shear as well as normal stress components (σ_{xx} and σ_{yy}) determines the load corresponding to the axial split. The low load carrying capacity of 60°, 75° and 90° specimens are due to the normal stress concentration (σ_{xx}) at the notch tips. The shear strength value 60° fibre orientation is minimum. In this case the split from the notch root (top) extends along the fibre direction towards the vicinity of inner loading point (bottom). The compressive stresses at the loading point also affect the strength in this case.

4.3.2 SHEAR BEHAVIOUR OF KEVLAR/EPOXY COMPOSITES :

Iosipescu shear tests were performed for 0° and 90° fibre orientations with respect to loading axis. The shear behaviour of Kevlar composites are somewhat different from that of carbon composites. Table 4.6 summarizes the shear modulus and ultimate shear strength these specimens. The stress-strain diagrams are given in Fig. 4.15 and load-displacement curves in Fig. 4.16. The failure pattern of kevlar and carbon composites are shown schematically in

Fig. 4.17. The 0° specimens of Kevlar composites deformed considerably more than the 90° specimens after initial damage. Also in the case of 0° specimen, the shear behaviour was fibre dominant, whereas, for 90° specimen it is matrix dominant.

FRACTURE AND FAILURE PATTERN :

For 0° specimens of Kevlar composite damage occurred in the test region between the notch roots. After initial damage the specimen deformed considerably. This corresponds to the flattened portion of the load (stress) -displacement plot. No cracks were formed in the vicinity of notches. The fibres during this yielding orient considerably and was taking most of the load in tension (Fig. 4.17a). Therefore, the specimen continued to take load and test was discontinued due to limitation on displacement that fixture can accommodate. Specimen texture at the test section was found to be rough after the strength test. This is expected due to a large number of matrix cracks (fine cracks) occurred at this location during strength test.

In the case of 90° specimens of Kevlar composites, beyond a certain load, damages were started between the notch roots. The specimen did not take much load after the damage was initiated. There was considerable deformation and damage growth till failure. The final fracture in all the cases were exactly between the notch roots as shown in Fig. 4.17b. In all the cases fibres came out of the matrix. Due to the failure of interface fibre brooming can be seen at the failed section. Also at the test section these fibres preserved the direction of shear after failure showing pure shear

KEVLAR/ EPOXY FIBRE ORIENTATION	SPECIMEN CODE	IN PLANE SHEAR PROPERTICS			
		INITIAL STRENGTH MODULUS (GPa)	SHEAR STRENGTH (MPa)	AVERAGE SHEAR MODULUS (GPa)	AVERAGE SHEAR STRENGTH (MPa)
0°‡	1 2 3	3.146 3.129 -	48.65 44.54 46.11	3.138	46.44‡
90°	1 2 3	2.3 1.875 -	41.11 43.77 37.998	2.088	40.96

‡ Specimen did not fail during Shear Strength Test.

TABLE 4.6 SHEAR PROPERTIES OF KEVLAR COMPOSITES

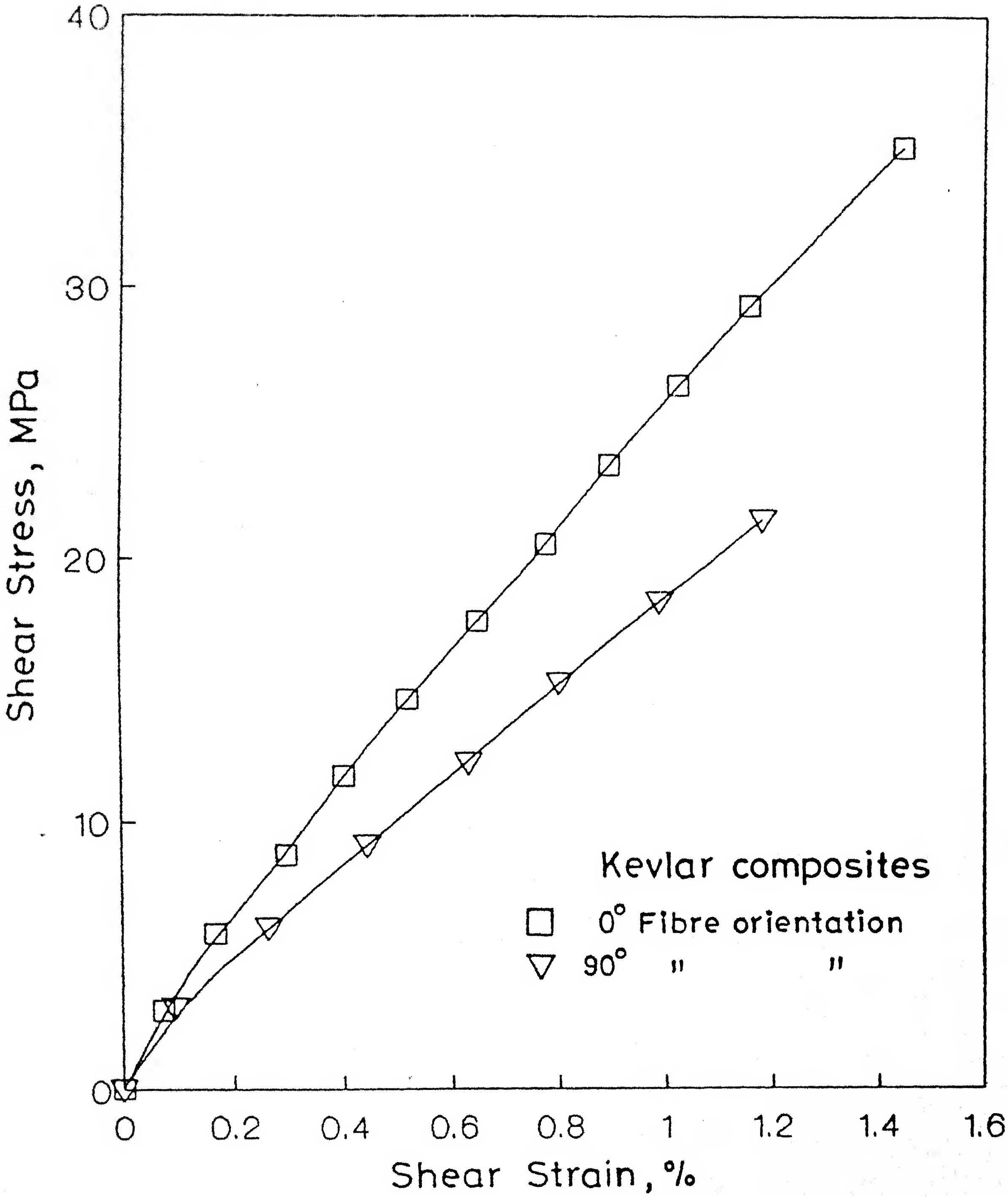


Fig. 4.15 Shear stress-strain diagram for Kevlar composites.

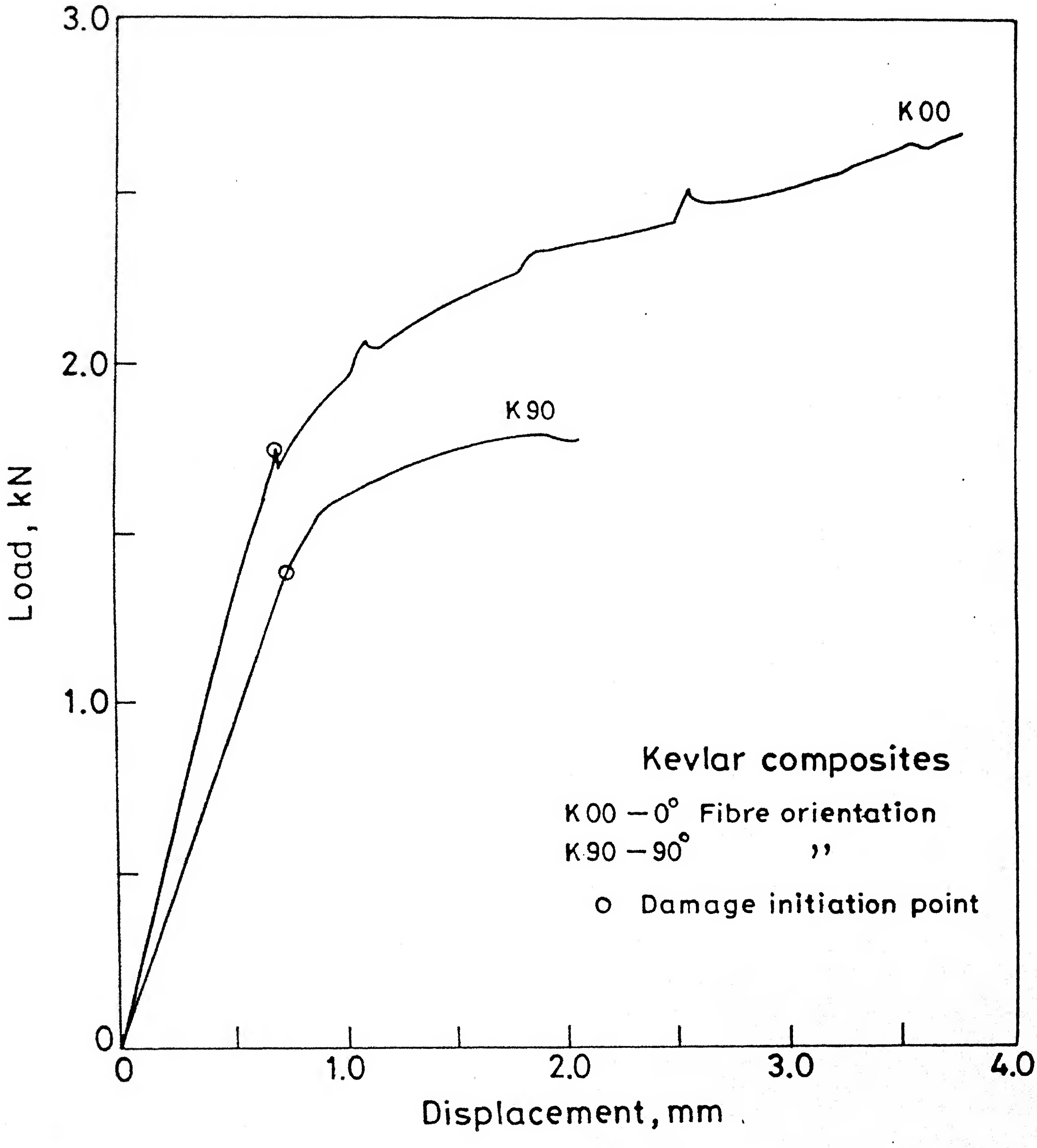


Fig. 4.16 Load-displacement diagram for Kevlar composites.

failure [37]. Photographs of Kevlar composite specimens fractured in shear tests are given in Fig. 4.18.

SHEAR MODULUS AND SHEAR STRENGTH :

From Table 4.6 we can see that the shear modulus of Kevlar composites are low compared to other materials. Their values are comparable with results available in literature [1,18,35]. The shear modulus of 0° specimens of Kevlar composites are higher than that of 90° specimens. This is expected due to the nonuniformity of shear stress distribution at the center line between the notch roots.

During shear strength tests, 0° specimens of Kevlar composite did nit fail. This can be related to the high toughens of Kevlar fibres. Also, there were no initial crack or axial split at the notch roots like carbon fibre composite. The axial split in unidirectional composites are associated with the stress concentration at the notches. But in the case of Kevlar composites, the excessive deformation at test section may relieve stress concentration at the notches. Moreover, due to the presence fibres oriented parallel to the loading direction (warp direction), it is difficult for cracks to emanate and propagate from the notch roots. Local orientation of fibres between notches took place during the deformation of specimen. Therefore, the specimen starts taking load in tension and the slope of the load-displacement plot increases after sometime (Fig. 4.16).

The 90° specimens of kevlar composites, yielded very low apparent shear stress at failure. The failure surface shows that the specimen failed in shear. The shear behaviour of 90° specimens were

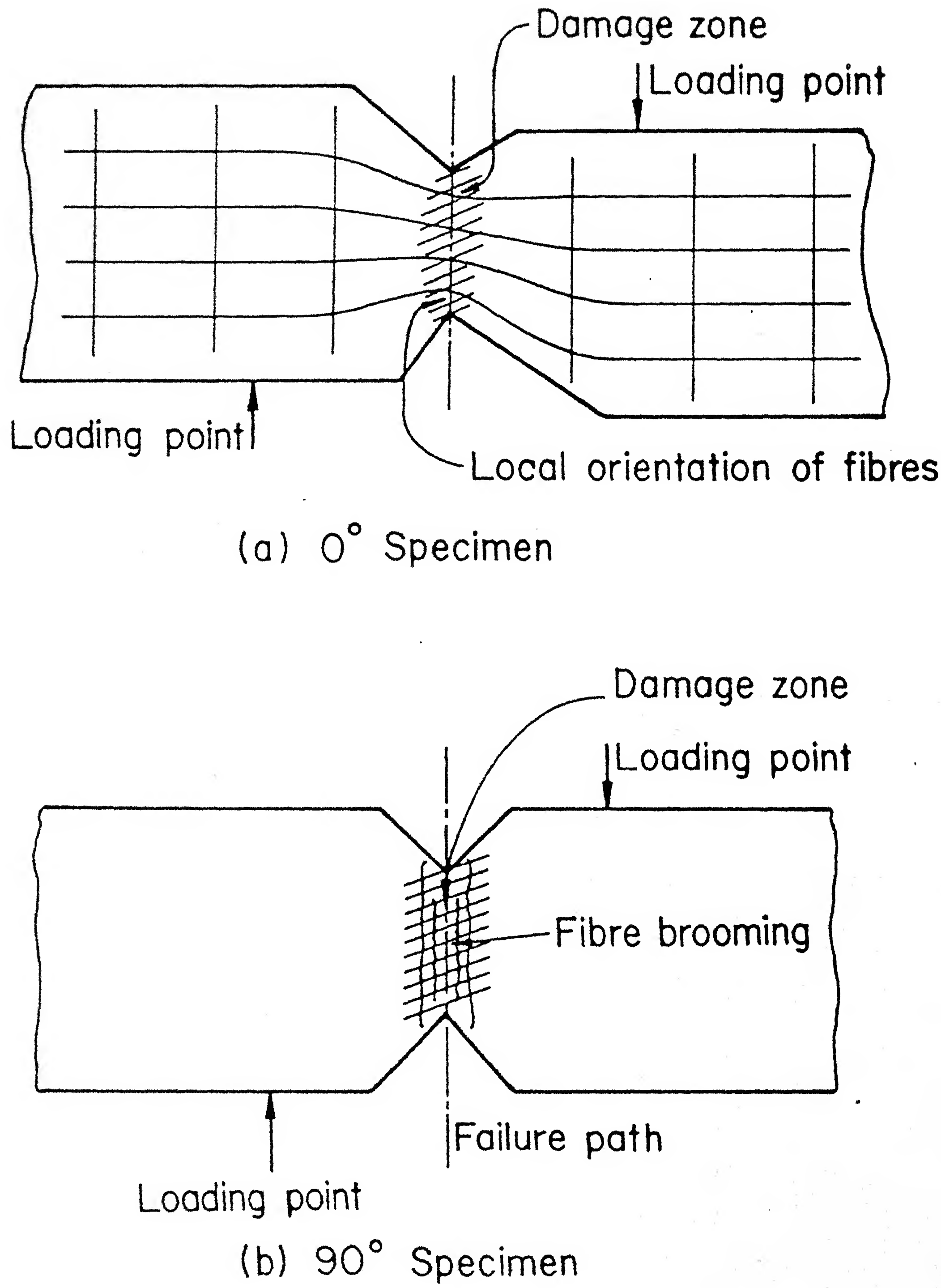


Fig. 4.17 Failure pattern of Kevlar composites

a)

b)

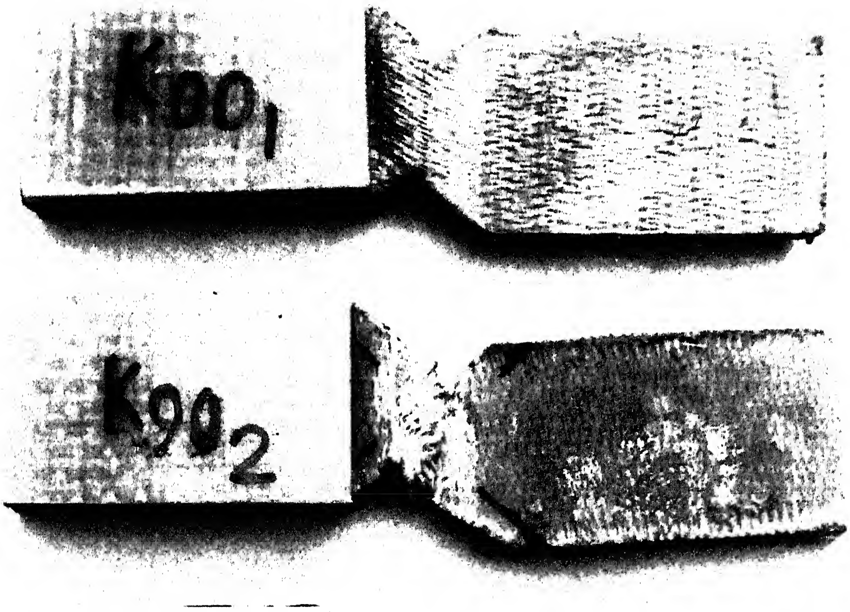


FIG. 4.18 FRACTURED IOSIPESCU SPECIMENS OF KEVLAR COMMPOSITES FOR FIBRE ORIENTATIONS Ø° AND 9Ø°.
a) Ø° SPECIMEN
b) 9Ø° SPECIMEN

matrix dominant. For most of the specimens, the failure initiated in the vicinity of upper notch tip with final fracture running parallel to fibres. In the case of Kevlar, the damage zone was wider than 90° specimens of carbon composites and fibres came out of matrix. i. e., the failure was at interface and the fracture surface was parallel to the fibre direction, showing a pure shear failure. Whereas, for carbon composite the fractured surface was smooth. In the case of Kevlar composite there was no crack or damage at the loading application point.

4.4 SHEAR MODE FRACTURE TOUGHNESS OF RANDOM GLASS COMPOSITE :

Most of the fracture toughness tests on composites, like those on homogeneous isotropic materials, are conducted in crack opening mode or Mode I. Fracture toughness tests on shear mode or Mode II are not important for homogeneous isotropic materials, because the loading conditions associated with the extension mode are considered to be severe for these materials. However, this may not be the case with fibrous composites which are generally week in shear. Thus the fracture toughness of composites in forward shear (Mode II) is very important from the design point of view. Most of the work on fracture of composite materials has, so far, centered around linear-elastic fracture mechanics concepts employing the analysis of crack tip region. There are practical difficulties in accurately analyzing the crack tip region for heterogeneous composites. In fibre composites, the crack does not propagate in a self similar manner and a number of energy absorbing processes (like matrix cracking, interface debonding, fibre breakage, fibre

pull-out etc.) occur in unpredictable degrees during fracture.

Only a few efforts appears to have been made to determine the Mode II fracture toughness of composites. This may be due to the difficulty in attaining a pure Mode II fracture in composites with the existing tests available for in-plane shear characterization. In most of the tests due to coupling and in-elastic behaviour of matrix or fibre-matrix interface the shear stress distribution at test section is being affected. Also the type of loading employed and the specimen geometry used control the applicability of these tests for Mode II fracture toughness determination. Out of these the use of double 'V' notched specimen (Arcan specimen or Iosipescu specimen) for shear mode fracture toughens is recent and has been found to be quite accurate [38,39,40,41].

Bank-Sills et. al. [38] used the Arcan specimen with central crack. Their test configuration also permits conducting experiments on Mixed mode fracture of composites. They conclude that the crack in the significant region (at specimen mid-length) provides favourable conditions to measure fracture parameters of material. Jurf and Pipes [39] used the Arcan test fixture to study the mixed mode interlaminar fracture of composites. They used specimens without 'V' notches and showed that the lack of uniform stress stress field within the unnotched specimen have no adverse influence upon test results due to the dominance of the singularity at the crack tip. Wang et. al [40] used the Iosipescu specimen for determining the Mode II fracture toughness of short-fibre SMC composites under shear loading. They clamped the ends of the specimen into the grips and loaded along the center line of the specimen. Both edge cracked and center cracked specimens were used

and found that the results obtained by these two were close. This proves the validity of these specimens for determining Mode II fracture toughness. they concluded that the shear mode fracture toughness of SMC composites were only one half of that of extension mode owing to the difference in fracture mechanisms involved in these two cases.

Kumosa and Hull [41] studied the use of Iosipescu shear tests for two-dimensional mixed mode fracture behaviour of aligned (oriented) composite materials. Their analytical studies concluded that the displacements at the crack tip indicate mixed mode fracture condition with significant Mode II domination. The analytical studies of Wang et. al. [40] showed that for random short fibre SMC composites the stress intensity factor associated with Mode I is significantly smaller and can be neglected. The difference in the oriented and random composites are expected due to high orthotropy ratio in the former which influence the stress distribution at test section and the stress intensity at the crack tip where as the latter is isotropic in plane.

Randomly oriented short fibre composite was selected for the present investigation which are macroscopically isotropic in plane, therefore the logical first choice to extend the concepts applicable to isotropic homogeneous materials. Also short fibre composites have become important material for the manufacture of many moulded components and structures. The fracture behaviour of these materials have been extensively studied Agarwal et. al. [42,43,44,45,46]. The extension mode fracture toughness of these materials has been investigated by both R curve method and through J

integral approach. Agarwal and Giare [43] determined the Mode II fracture toughness of this material and concluded that the Mode II fracture toughness was nearly half of that of Mode I. These authors used single edge notched specimens. The testing fixture used was some what similar to that used by Wang et. al. [40]. Compliance matching procedure was used to calculate the strain energy release rate G_{IIC}.

In the present investigation, Iosipescu specimens without any 'V' notch or groove were used for determining the Mode II fracture toughness of random glass composites. Double edge notched (DEN) specimens were used and shear loading is obtained through Iosipescu shear test (Wyoming) fixture. The use of double edge notched specimen is preferred over single edge notched specimen for the type of loading employed to attain shear. Although no 'V' notches or grooves were cut in the specimen to attain uniform shear at test section because it is expected that the singularity of the sharp notch controls the shear stress distribution between the machined slit cracks. This study assesses the suitability of Iosipescu shear test fixture for determining Mode II fracture toughness. The specimen used and the test procedure have been given in Chapter 3.

4.4.1 J INTEGRAL APPROACH :

The J integral proposed by Rice is an attractive parameter to characterize the crack tip conditions. Due to the path independence of J integral, the integration path can be chosen away from the crack tip without compromising on accuracy. This avoids the difficult problem of accurate determination of stress near the crack

tip. For composites, It has an additional advantage is that it dos not require measurements of instantaneous crack lengths which is difficult to define or measure. Because in composites the fracture process proceeds by a large number of micro-cracks with different orientations ahead of the crack tip due to debonding, matrix cracking and fibre breaks.

Applicability of J integral for short fibre and fabric reinforced glass composites has been investigated by Agarwal et. al. [45,46,47,48]. Their studies concluded that the J integral approach is very convenient to study the fracture toughness (Mode I) of composites. The applicability of J integral for shear mode fracture is not fully developed and only a few work has been done on composites to determine J_{IIC}. Wang et. al. [40] used J integral method to numerically calculate the fracture toughness in Mode II. They concluded that the results obtained by this method for both center cracked and edge cracked Iosipescu specimen were in good agreement. They also reported good agreement between the numerically determined and experimentally measured J_{IIC} for the above mentioned crack cases. But they have not explained the experimental procedure or the method of analysis to determine shear mode fracture toughness J_{IIC}.

Experimental evaluation of J integral was accomplished quite easily by considering the load-deflection curves of identical specimens with varying crack lengths. The material property J_C can also be determined with two specimens, that differ only in crack area, from the load-displacement curves. Early and Burns [49,50] proposed this method for isotropic materials for determining

fracture toughness in crack opening mode. This method is used in the present investigation for determining the J_{IIC} (i.e., in forward shear mode) of random glass composite.

According to this method J_C is calculated from the load-displacement diagram of two specimens that differ only in crack area. Fig. 4.19 shows a schematic load-displacement curve of specimens with crack area A (curve 1) and A + dA (curve 2). J_C is calculated using the relation

$$J_C = \oint 1/dA \int P \times dx \qquad 4.2$$

where,

$\oint P \times dx$ = the enclosed area between the two load-displacement curves 1 and 2

dA = the difference in crack area

The crack area can be easily calculated from an average crack length and specimen thickness. The specimen used was of 2 mm thickness with half crack lengths of 2,3,4,5,6,7 and 8 mm.

FRACTURE AND FAILURE PATTERN :

The failure modes were found to be different for specimens with half crack lengths 'a'> 6 mm and 'a' < 6 mm. Fig. 4.20 shows their failure pattern schematically. In the case of 'a' > 6?mm, damage initiated at the notch root and spread between the notch roots. The failure was almost in a vertical plane between the notches (Fig. 4.20a). For 'a' < 6 mm, the failure initiated at the notch roots extended in a direction slightly away from the vertical line joining the notch roots in most of the cases (Fig. 4.20b). Considerable damage occurred in these cases and damage zone was

bigger. For specimens with half crack lengths 2 and 3 mm, slight edge crushing was noticed in most of the specimens and damage occurred directly below the inner loading points. Fig 4.20c shows the damage due to compressive stress induced by loading points schematically. Also for these specimens the initial damage from the root notch propagate at an angle greater than that of higher crack length specimens from the center line. In some of these specimens damage also occurred above the notch root from the notch flank nearer to the corresponding inner load point. A photograph of the fractured specimens are presented in Fig. 4.21

4.4.2 MODE II FRACTURE TOUGHNESS, J_{IIC} :

The fracture toughness results were analyzed using the Early and Burns method [50]. According to this method the material property J_c can be determined with two fracture specimens, that differ only in crack area, from the load-displacement diagram. Specimens with 1 mm difference in half crack length were selected for analysis, i. e., 2 mm and 3 mm, 3 mm and 4 mm etc. Typical load-displacement diagrams of Iosipescu fracture tests are given in Fig. 4.22. To determine J_c it is necessary to identify the points of crack initiation on the load-displacement records. During fracture tests on most of the specimens, load falls at the onset of crack propagation. The curve is almost linear till this point and the integration along the curve is carried only upto the point where the slope changes abruptly. This was found to be suitable for the curves obtained in all cases. In the case of half crack lengths with 'a' > 5 mm, the specimens did not take load after this point. But for half crack lengths 'a' < 5 mm, in a number of cases, specimen took

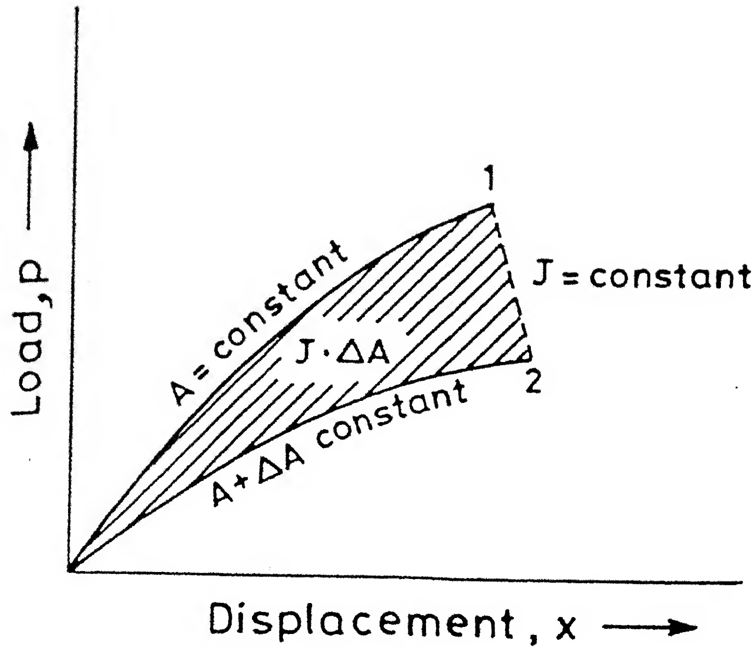


Fig. 4.19 A schematic load-displacement diagram.

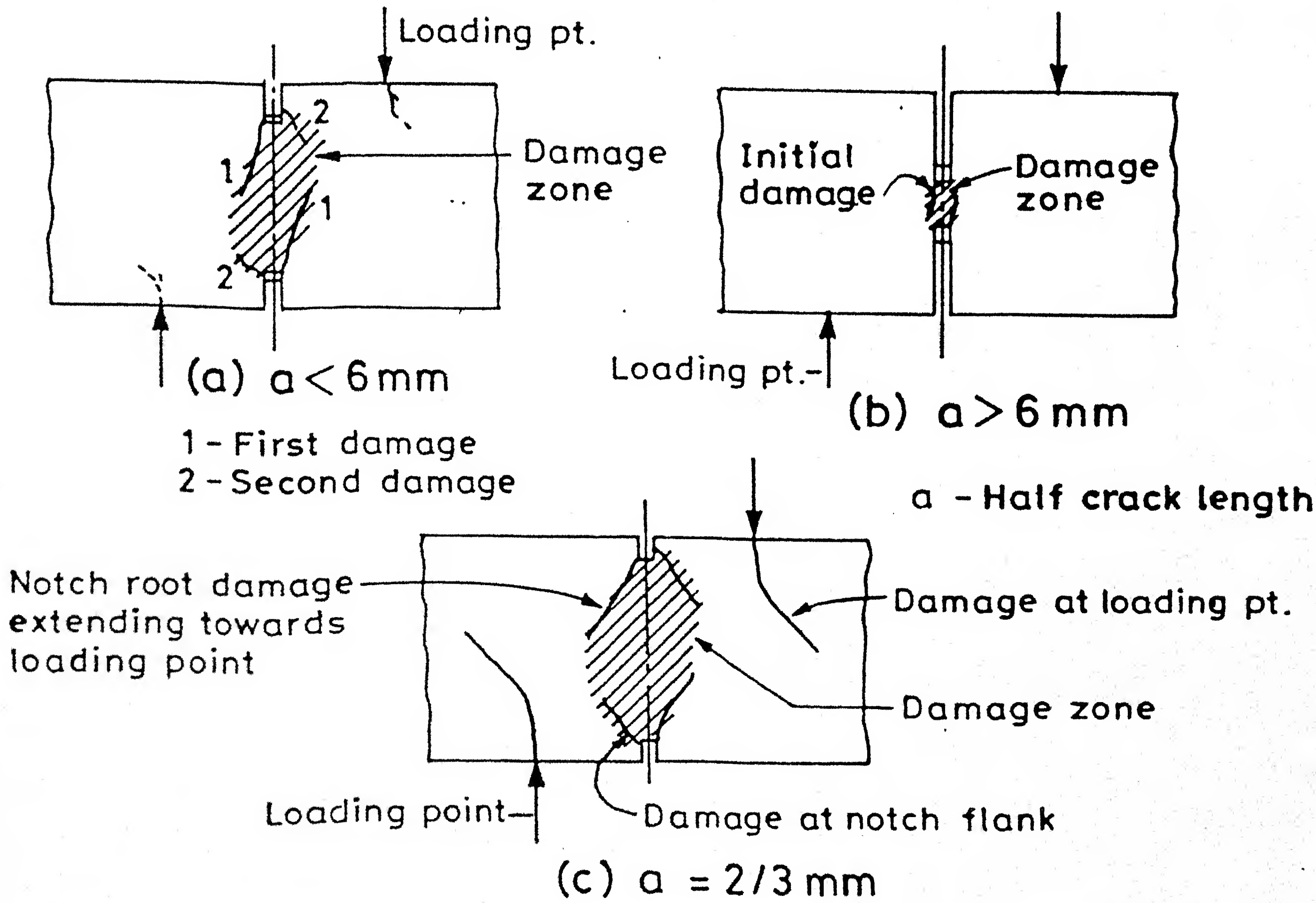


Fig. 4.20 Failure patterns of fractured specimens in mode II fracture test.

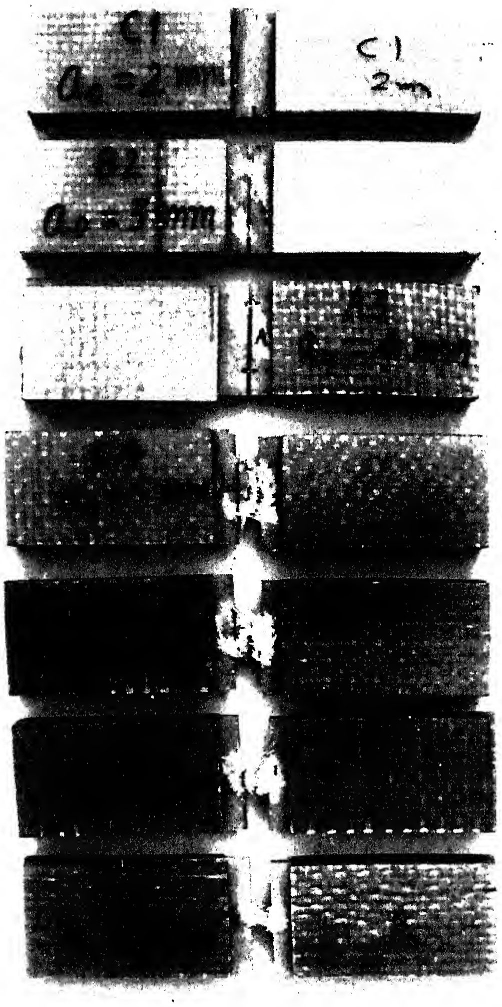


FIG. 4.21 FRACTURED SPECIMENS OF RANDOM GLASS COMPOSITES FOR HALF CRACK LENGTHS FROM 2 mm TO 8 mm.

load more than the load corresponds to the first load drop.

The specimens used were of half crack lengths varying from 2 mm to 8 mm in steps of 1 mm. Fig. 4.23 gives a typical load-displacement diagram of fracture specimens with half crack lengths 4 mm and 5 mm. The hatched area in this figure corresponds to the integral quantity in equation 4.2. The difference in crack area was found from the average crack lengths and specimen thickness for the two specimens considered. Table 4.7 summarizes the results of Iosipescu fracture toughness test. It can be seen that the shear mode fracture toughness J_{IIC} is almost constant (approximately 26 kJ/m^2) between half crack lengths 2 mm and 6 mm. This value can be compared to that obtained by Agarwal and Giare [43] (24.5 kJ/m^2). Also this value is only one half of extension mode fracture toughness J_{IC}. For 'a' = 2 mm, J_{IIC} was slightly high, whereas, for 'a' > 6 mm, there was considerable drop. These results were representative of the results obtained from the different combination of test specimens. It was found that in some cases J_{IIC} obtained were significantly varying from the values given in Table 4.7. Since the present investigation is only a preliminary investigation to asses the suitability of the test and analysis used for determination of Mode II fracture toughness of composites, an accurate determination of J_{IIC} was not attempted. But these results give light to the procedure and precautions that should be taken care for an accurate determination of J_{IIC} of composites.

The difference in the J_{IIC} is expected due to large variation in shear stress distribution for different crack lengths and the effect of load point induced compressive stresses. They can

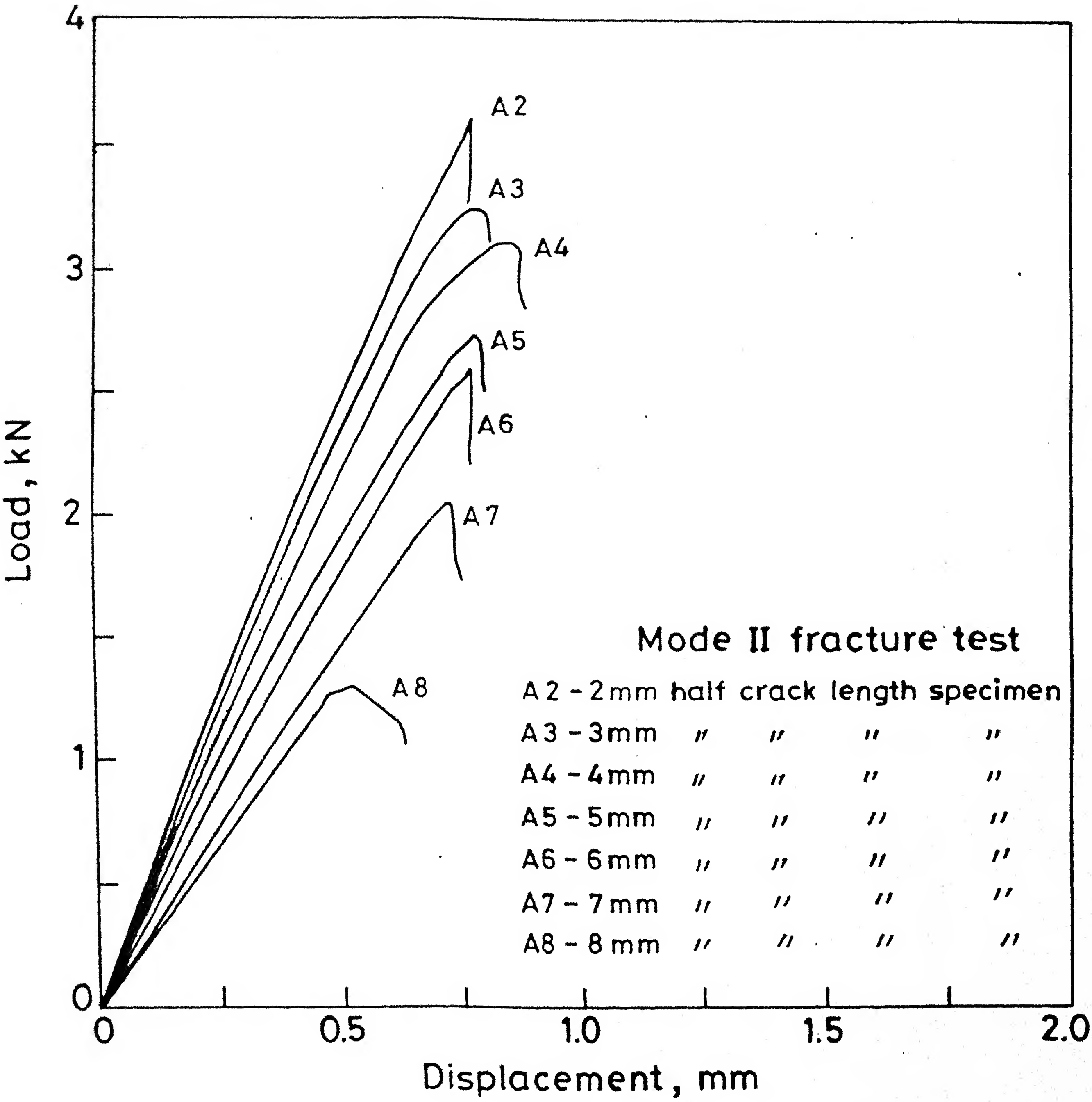


Fig. 4.22 A typical load-displacement diagram for mode II fracture test.

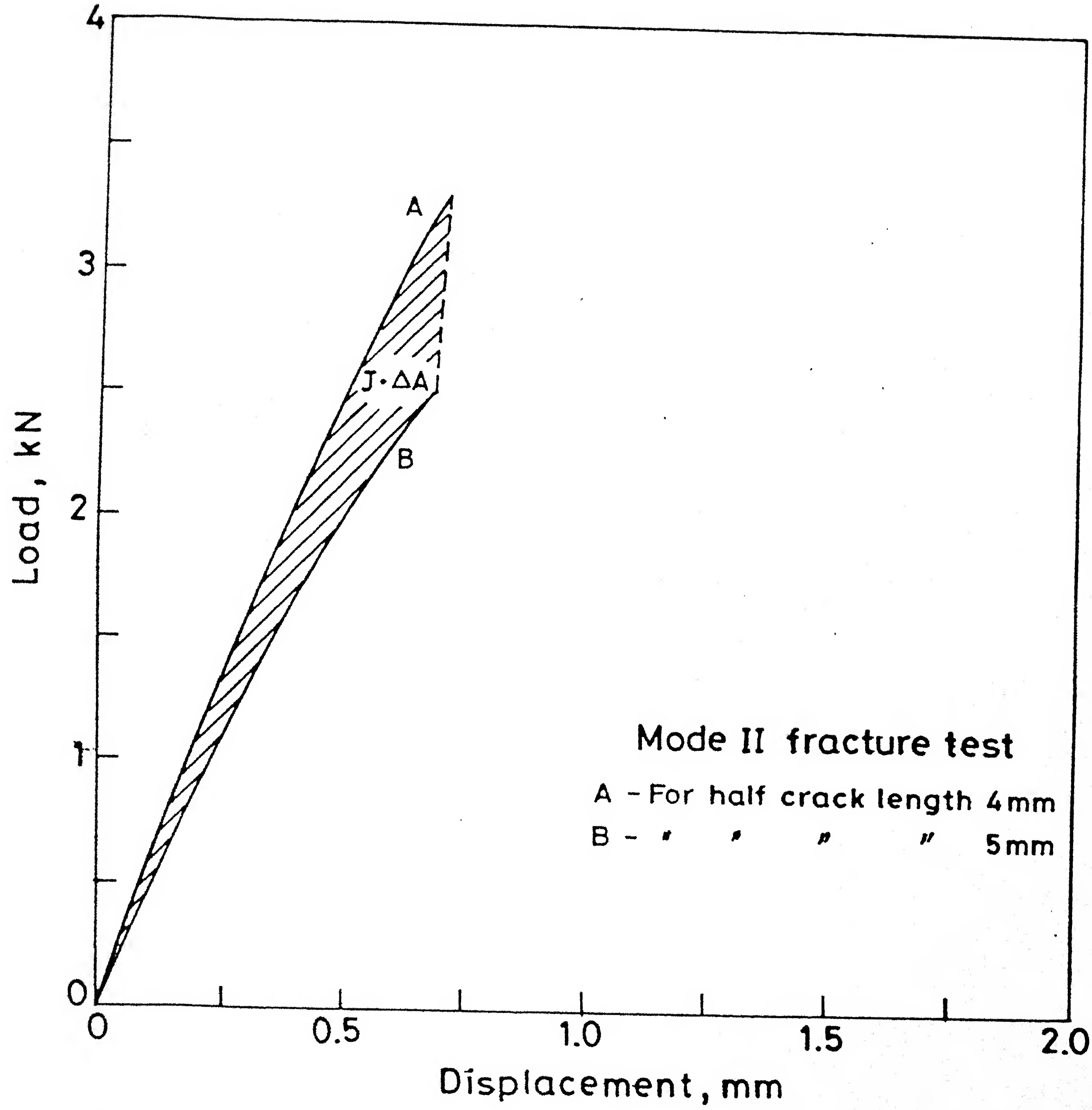


Fig. 4.23 Load displacement diagram showing the measurement of J_{IIC}.

also be accounted for the damages occurring away from the crack tip (at inner loading point locations, near the notch flanks etc.) and the fracture mode (Mode II or mixed mode, Mode I and Mode II).

The shear stress distribution at test section will be parabolic for Iosipescu specimens without any notch or crack. The 90° 'V' notches made to a depth of 20 % or 25 % of overall specimen width improves the nonuniformity of test section and results in an almost uniform stress field. The effect of increase or decrease in notch angle is equivalent to the decrease or increase of notch depth. i. e., the shear stress at the notch root increase as we increase the notch depth or decrease the notch angle. Thus the use of slit cracks (notch angle 0°) instead of 'V' notches (notch angle $> 0^{\circ}$) definitely increases the shear stresses at the notch root for the same depth. Fig. 4.24 gives the expected shear stress distribution at the test location for 3 mm, 5 mm and 7 mm half crack lengths. The shear stress distribution for 2 mm and 3 mm half crack lengths is expected to be almost uniform due to the notch singularity. For specimens of 4 mm and 5 mm crack lengths, due to the notch singularity at increased depths, shear stress at the notch root will be more than earlier case. This leads to slight variation in shear stress at test location. This nonuniformity increases as the half crack length increase from 5 mm to 8 mm. For unnotched specimen, the maximum shear stress is at the center of the specimen at test section. But as the slit crack is introduced due to notch singularity, the shear stress at notch root will be more than that at specimen center and it is proportional to the notch depth. Therefore, for higher crack lengths, the variation in shear stress between notch roots will be more and the shear stress at the center

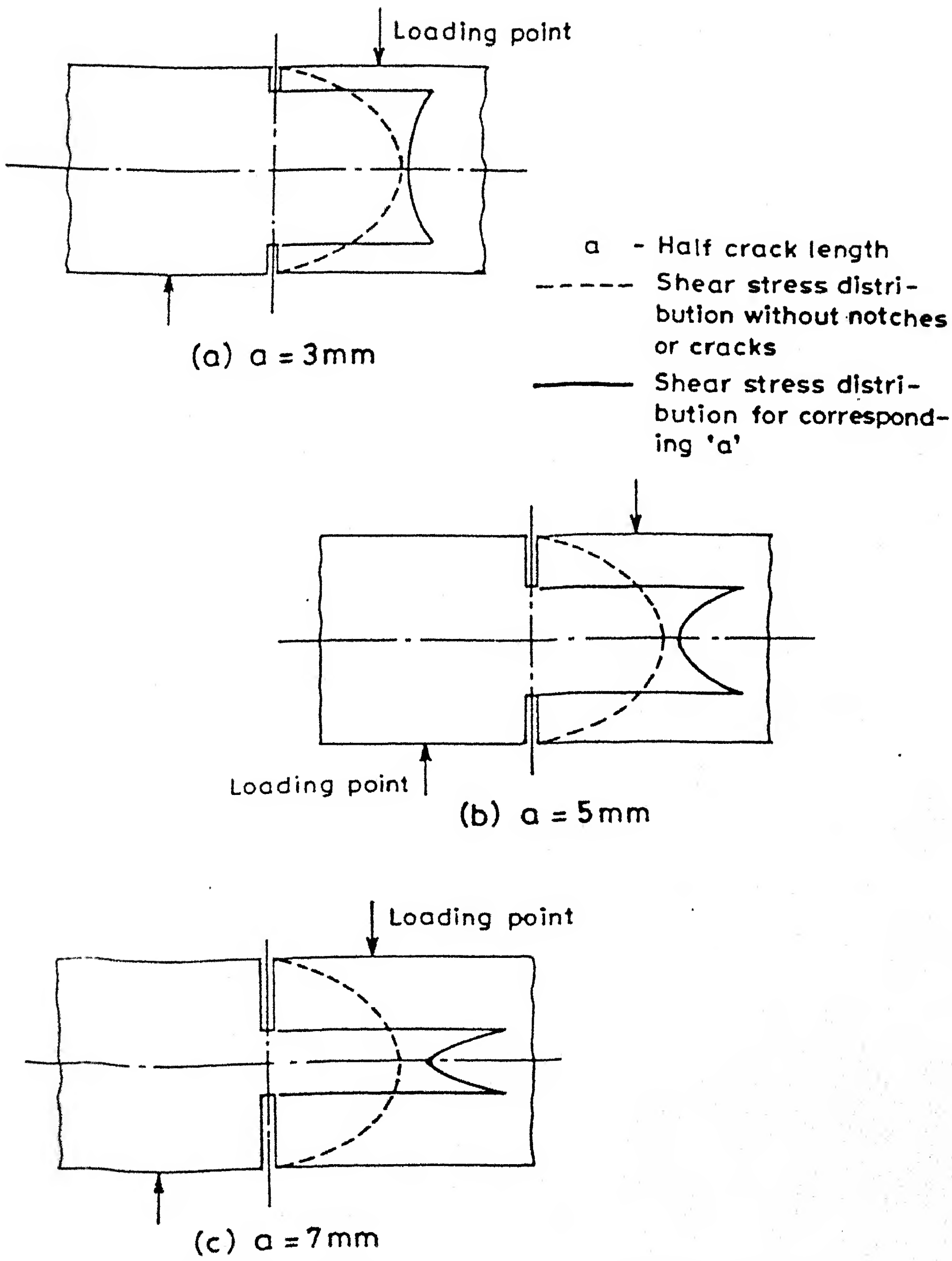


Fig.4.24 Expected shear stress distribution at test section for fracture specimen.

will be more than that for an unnotched specimen.

Wang et. al [40] and Kumosa et. al. [41] reported that the fracture of Iosipescu specimen is not in pure shear mode. These specimen failed in a mixed mode with Mode II domination during fracture test. Since the J_C corresponds to Mode I is higher than that of Mode II, The value obtained for a mixed mode fracture will be always higher than that of pure Mode II. Thus for an accurate determination of J_C, the fracture mode has to be properly interpreted and correspondingly a suitable fracture criterion (for mixed mode) has to be applied. For isotropic materials the fracture in mode I is perpendicular to the loading direction and in Mode II, it is along the loading direction. For composite materials, the crack may not propagate in a self similar manner in the above mentioned way. But the damage at test section (between notches) causing failure should extend along and perpendicular to the loading direction for fracture in pure Mode II and Mode I, respectively.

In the present study, observations of fracture behaviour of specimens with different half crack lengths shows that the effect of Mode I increases as the crack length decreases. i. e., for higher crack lengths ('a' > 6 mm) the failure is almost through Mode II, whereas, for 'a' < 6 mm the effect of Mode I is pronounced. In the case of 'a' > 6 mm, the average shear stress at significant section is high and damages are centered between the notches. For specimens with half crack lengths 4 mm to 6 mm, the damages initiated at the notch roots and propagates in a direction slightly away from the specimen center line. The direction of damage extends towards the inner loading point directions (Fig. 4.20c) for specimens with

half crack lengths 2 mm and 3 mm. Thus for these specimens damage extends more away from the center line of the specimen.

The effect of loading point induced compressive stresses during fracture toughness tests is expected to vary with half crack lengths. For 'a' > 6 mm, The load applied is comparatively small at failure and the shear stress distribution is controlled by the stress singularity at the notch root. i. e., since the notch root is away from the loading point and due to higher crack length the stress at notch root will be high. Therefore, the effect of loading points can be neglected. For lower crack lengths ('a' < 6 mm), the compressive stresses will be more and the stresses at the notch root is comparatively less. This is more pronounced at half crack lengths of 2 mm and 3 mm. Thus for these cases the effect of loading points can not be neglected.

For Iosipescu specimens pure shear is only along the specimen center line and the bending induced normal stress (σ_{xx}) is present away from this center line. Shear force and bending moment diagram for Iosipescu loading are given in Chapter 2 (Fig. 2.1). For lower crack lengths ('a' < 6 mm) the bending stresses will be more and their effect near the notch will be to load it in extension mode. This effect will be more for half crack lengths 2 mm and 3 mm. Thus for these cases the effect of loading point and the bending induced normal stresses increases the chance of fracture in Mode I compared to those higher crack length specimens. Thus the damage propagating away from the center line of specimen is expected due to the influence of Mode I during fracture. In the case of specimens with 'a' > 6 mm, both the above mentioned affects are small and the failure takes place exactly between the notches.

The extension mode fracture toughness J_{IC} is more than that corresponds to shear mode fracture. Also for lower crack lengths specimens, damages occurred away from the crack tip also account for the measurement of J_{IIC}. Therefore, it can be concluded that the variation of J_{IIC} with crack length is expected because the effect of Mode I varies as the crack length is increased and less and less damages occurred out side the test section. Also the shear stress distribution at significant section and the effect of loading point controls the fracture mode and correspondingly the experimentally measured J_{IIC} for Iosipescu fracture test.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

Iosipescu shear tests were performed on all materials considered for present study. From the results obtained during the shear tests , the following conclusions can be drawn.

1. The crushing of specimen edge at inner loading points were alleviated by using suitable specimen design and employing tabs fixed to their ends. Such specimens worked satisfactorily.

2. Randomly oriented glass fibre composite showed superior shear behaviour compared to glass fabric reinforced glass composites. Coarse glass composite yielded low apparent shear strength compared to other two.

3. Shear strength and modulus of 0° specimens of Kevlar and carbon composites were higher than those of 90° specimens. This is expected because of the non-uniform shear stress at test section.

4. The 0° specimens of Kevlar deformed considerably and resisted failure at test section. Whereas, 90° specimens failed exactly between the notches and the fracture surface was parallel to the fibres.

5. During strength tests for unidirectional composites, failure started at notch roots (axial split) and extended along the fibre direction, away from the inner loading points. Their fracture and failure behaviour can be grouped in to three types, i. e., between 0° to 30°, at 45° and those between 60° to 90°.

6. The discrepancy between the theoretically and experimentally measured values of shear modulus of carbon composites were expected due to non-uniformity of shear stress distribution at

significant section and coupling effects.

Fracture toughness tests in shear mode were performed on random glass composite and has been investigated through J-integral approach. The method suggested by Early and Burns was used for determining J_{IIC}. Based on their results, the following conclusions were drawn.

1. The fracture and failure modes of failed specimens were examined closely for different crack lengths. It seems that the fracture of these specimens occurs in a mixed mode (Mode I and Mode II) with Mode II domination.

2. For half crack lengths 'a' > 6 mm, the damage was confined between the notches showing domination of Mode II. For 'a' < 6 mm, the failure initiated at the notch roots propagates in a direction away from the center line between notch roots. In the case of specimen with 'a' < 3 mm, these damages extended towards the inner loading points.

3. The J_{IIC} measured using Early and Burns method was found to vary with crack length. This is expected due to the pronounced influence of Mode I for low crack length specimen which decreases as crack length increases. It seems that the bending induced normal stresses, loads the crack in opening mode and the failure path of the specimen deviates from the plane of shear loading.

4. The edge crushing at inner loading points and damages occurring away from the crack tips absorb energy and result in a higher fracture toughness value. These effects were found to be pronounced for 'a' < 5 mm.

SCOPE OF FUTURE WORK :

I. EXPERIMENTAL

1. The effect of variation of specimen geometry (notch angle, notch depth and notch root radius etc.) can be studied for different types of reinforcement. Photoelastic studies for the same are possible through birefringence technique. The effect of fibre orientation on stress or strain distribution at significant section can be studied using this technique effectively.

2. Shear mode fracture toughness of different types of reinforcements can be investigated. Single edge notched or double edge notched specimen can be used. Also specimens with slit cracks at 'V' notch roots can be employed for the investigation. Their fracture mode has to be carefully examined for interpreting the results. A mixed mode fracture criteria can be applied for accurate determination of J_{IIC}.

3. The shear fatigue and fracture of composite can be studied using Iosipescu test fixture.

II. NUMERICAL

1. Analytical investigation can be performed for Iosipescu shear test specimen to study the effect of specimen geometry, loading point distance and fibre orientation. Correction factors for shear modulus can be found in all cases by considering the actual stress distribution at significant section.

2. Finite element analysis for ' two body contact' problem can be applied to the Iosipescu test fixture. This take care of the loading point effects and simulates the experiment. More accurate

prediction of correction factors for shear modulus are possible in this case.

3. Numerical investigation can be performed for the shear mode fracture toughness specimens with double edge notch, single edge notch and slit cracks at the roots of 'V' grooves. The J-integral can be determined analytically. The effect of fracture mode (Mode I and Mode II) can be studied in all cases. These results may help to standardize an experimental procedure to determine shear mode fracture toughness of composites using Iosipescu test fixture.

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